The Effect of Retarder on Gelation Time and Stability of Polyacrylamide Chromium (III) Gel System

by

Muhammad Hasan Muhammad Al-Nashmi

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

June, 1997

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

THE EFFECT OF RETARDER ON GELATION TIME AND STABILITY OF POLYACRYLAMIDE CHROMIUM(III) GEL SYSTEM

BY

MUHAMMAD HASAN MUHAMMAD AL-NASHMI

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
In

PETROLEUM ENGINEERING

JUNE 1997

UMI Number: 1398758

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

COLLEGE OF GRADUATE STUDIES

This thesis, written by Mr. Muhammad Hasan Muhammad Al-Nashmi under the direction of his Thesis Advisor and approved by his Thesis committee, has presented to and accepted by the Dean of the College of Graduate Studies, in parial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Petroleum Engineering.

Thesis Commitee

Dr. Abdulaziz A. Al - Majed
Thesis Advisor

Dr. Khalid Al - Fossail
Member

Sk. Asrof Ali

Dr. Shaikh Asrof Ali
Member

Dr. Abdulaziz A. Al - Majed
Department Chaiman

Dr Abullah Al - Shehri
Dean, College of Graduate Studies

Date : 6/9/97

This Thesis is dedicated to my Parents, Wife, Children, sister, teachers friends and all my be loved

ACKNOWLEDGMENT

All praise be to the Almighty, ALLAH, with whose gracious help it was possible to accomplish this work. After and after that, Acknowledgment is due to King Fahd University of Petroleum and Minerals for the support throughout my study

I wish to express my appreciation and my great thanks to Professor Abulaziz A. Al - Majed who served as my major advisor. I wish also to thanks the other members of my Thesis Committee Dr. Khalid Al - Fossail and Dr. Shaikh Asrof Ali.

My words of thanks are due to Mr. Mansour Al - Saber for his support and encouragement during the period of my study.

Sincere thanks are due to both Petroleum engineering laboratories supervisor Mr. Mansour and Petroleum engineering Lab. technicians Mr. Abdulsamad, M. Iddris, Mr. Mosa and Mohammadin.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

ملخص الرسالة

اسم الطالب بالكامل : محمد حسن محمد النشمي

عنوان الرسالة : أثر المعوق على زمن تكون الهلام لنظام البولي اكريلاميد – كروم

حقل التخصص : هندسة البترول

تاريخ الشهادة : يونيه ١٩٩٧م

حديثا استخدم نظام البولي اكريلاميد – كروم كعامل تحكم في إنسياب السوائل في المكامن من اجل تحسين نسبة الماء الى الزيت أثناء عملية الغمر بالماء ، كما استخدم كعامل تحكم في الابار التى إبتليت بإندفاع الماء نحوها بشكل مخروطي • يعمل الهلام على توجيه حركة الماء في المناطق ذات المسامية العالية والصدوع الى المناطق المحددة للغمر مؤديا الى تحسين عملية إزاحة الزيت •

كلما إرتفعت درجة الحرارة قل الزمن اللازم لتكون الهلام مشكلا عائقا أمام استخدام الهلام عند درجات الحرارة العالية • بحثت هذه الدراسة أثر لاكتيت الصوديوم كمعوق في تأخير زمن تكون الهلام عند درجات حرارة مختلفة • كما قيست لزوجة الهلام عند درجة حرارة وزمن ومعدل قص مختلفة• كما بحثت هذه الدراسة فعالية الهلام في سد المسامات وذلك بضخ الهلام خلال عينات لبية من الاحجار الجيرية والرملية •

نتائج هذه الدراسة أثبتت فعالية لاكتيت الصوديوم في تأخير زمن تكون الهلام من ساعات الى أيام اعتمادا على درجة تركيزه • كان الهلام مستقرا خلال الفترة التي أجريت فيها الدراسة • كما أثبتت النتائج أن لزوجة الهلام تزداد مع الزمن وتزداد إذا زادت درجة الحرارة ، كما أن اللزوجة تقل عند زيادة معدل القص • بينت الدراسة فعالية الهلام في سد المسامات الى أقل من ١٪ من المسامات الأصلية • وأخيرا يمكن استخدام هذه الدراسة كدليل عند تصميم عملية أو معالجة وقف إنتاج الماء من الابار •

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

يونية ١٩٩٧م

THESIS ABSTRACT

NAME OF THE STUDENT : MUHAMMAD HASAN MUHAMMAD AL - NASHMI

TITLE OF STUDY : THE EFFECT OF RETARDER ON GELATION TIME AND STABILITY OF POLYACRYLAMIDE CHROMIUM(III) GEL SYSTEM

MAJOR FIELD : PETROLEUM ENGINEERING

DATE OF DEGREE : JUNE 1997

Recently the polyacrylamide chromium(III) gel system has been used as a flow control agent to improve the water oil ratio(WOR) in water flooding operations and wells plagued by water conning. Gel divert the movements of water from high permeability thin zones and fractures to the bypassed regions leading to improved sweep effeciency.

As temperature increases gelation time becomes shorter limiting the application of the gel at high temperature. In this study an evaluation of the effectiveness of sodium lactate in delaying the gelation time at different temperatures was investigated. The gel viscosity at different temperatures, times and shear rates was measured. The plugging effeciency of the gel was studied by injecting the gel solution through sandstone and limestone cores.

Results obtained showed that sodium lactate was effective in prolonging the gelation time from hours to days depending on its concentration. The gel was found to be stable during the period of study. The gel viscosity increased with time and increased if the temperature was increased. The gel viscosity decreased if shear rate was increased. The permeability of the cores was reduced to less than 1.0 % of its original value. The results obtained could be used as a guide in the design of water shutoff treatments for field application.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia

June 1997

CHAPTER 1

CHAPTER 1

INTRODUCTION

Improved oil recovery (IOR) refers to any method used to recover more oil from reservoirs than would be produced by primary recovery methods. The estimated world crude oil reserves are very large compared to the produced. The estimated amount of unrecoverable oil throughout the world is approximately 2.0 trillion barrels. Enhanced oil recovery can add a significant amount of oil to the world supply. The lack of sufficient natural drive and the decline of oil production led to the introducing of the artificial drive methods(Enhanced oil recovery methods). In the early days of oil production the reservoir is allowed to produce until the amount of oil production rate becomes uneconomic. This period of oil production is known as primary recovery. Secondary recovery is the production phase in which the enhanced oil recovery processes are used. In some reservoirs, initial production is by natural drainage followed by water injection (secondary recovery) after that it will be followed by tertiary recovery. Therefore the terms Secondary and Tertiary recovery are only of historical interest and describe the order of the methods used to recover oil rather than being related to their

characteristics. Improved oil recovery can be achieved by processes carried out in the production wells (Steam stimulation) or in injection wells (water, steam and polymer floods and gas injections).

1.1- THERMAL RECOVERY

The primary objective of the thermal recovery is to decrease the viscosity of heavy oil by injection of steam, injection of air (in-situ combustion) and steam stimulation. In these processes, the driving forces are enhanced.

1.1.1- Steam Stimulation

In steam stimulation (also known as cyclic steam injection, steam soak or huff and puff) process, steam is injected through the well into the reservoir. The well is shut-in for a few days to allow the heat to spread into the reservoir. The reservoir temperature will increase resulting in increasing of heavy oil mobility. During steam injection, the rock matrix and the oil undergo chemical alterations due to the high temperature and pressure. Rock matrix decomposition has been observed during steam injection in carbonate reservoirs causing changes in the permeability. Formation of carbon dioxide resulting from chemical reaction will form a secondary gas cap. The process of steam injection will lead to an

increase in oil production. Other important advantages of steam stimulation are thermal expansion of fluids, compression of gas saturation, reduction of residual oil saturation and cleaning wellbore damage. Moreover, steam stimulation is less expensive than steam injection but it has less recovery than steam injection. After steam stimulation, the operator will shift to steam flooding process.

1.1.2- Steam Flooding

In steam flooding (or hot water injection), hot water is injected through the injection wells of certain arrangements to the reservoir. In the same time oil is produced from adjacent production wells in the same reservoir. Steam and hot water are both excellent heat carriers. Hot water is preferred in shallow reservoirs containing oil of low viscosity ranges from 100 cp to 1000 cp. However steam injection is preferred over hot water injection because of the excessive hot losses in the surface, wellbore and reservoir rocks. Hot water will increase the temperature of the zone of injection wells. While steam is moving away from the injection wells, its temperature will drop and steam will expand because of pressure drop. At some distance from the injection wells, steam will condense and form a hot water zone which will displace the oil. Changes such as thermal expansion of oil, reduction of oil viscosity, reduction of residual saturation and

change of relative permeability are caused by this method. The advantage of steam flooding is that it can be applied to a wide variety of reservoirs.

1.1.3- In-situ Combustion

There are two different types of in-situ combustion. The forward combustion in which the injected air in the production well is ignited. The combustion front moves away from the injected well through the reservoir by continuos injection of air. In this case the temperature is distributed from the injection well to the production well. However, in the reverse combustion the air is injected from the production well and the air injected from injected well is stopped. Therefore, the oil bank will move in reverse direction through the burned zone. The production well of the forward combustion will be a production well when the process is switched to reverse combustion. The principle of in-situ combustion is to generate heat inside a hydrocarbon bearing formation. In a reservoir containing heavy oil part of the oil is burned to improve the flow of the unburned part by reducing its viscosity. The heat created is sufficient to raise the temperature of the rock to enable the combustion front to self-propagate after initial ignition.

2- CHEMICAL PROCESSES

1.2.1- Surfactant-Polymer Injection

The purpose of surfactants flood is to reduce the interfacial tension and allow a better oil displacement compared to that displaced by water alone. Two steps are involved in this process, the injection of surfactant slug and injection of polymer mobility buffer. The surfactant slug can be of high or low concentration. Moreover, alcohols, water, hydrocarbon and salt can be added to the slug. In field application, it is difficult to control surfactant-polymer systems because of continues chemical reaction and changes that occurs during slug movement through the reservoir.

1.2.2- Polymer Flooding

Polymer is added to the injected water as a thickening agent to increase its viscosity. Using polymer in enhanced oil recovery process reduces the volume of water required to reach the ultimate residual oil saturation and increase sweep efficiency due to the improved mobility ratio. Three types of polymers are used, polyacrylamide, polysccharides, and ethylene polyoxide. The most popular polymer used, however, is polyacrylamid. The molecular weight of Polyacrylamides ranges from a few hundred thousand to many millions. Polymer

flood give significant recovery when compared to water flood only in certain reservoirs.

1.2.3- Carbon Dioxide Injection

The objective of carbon dioxide injection is to achieve a miscibility between carbon dioxide and oil. This process will reduce the viscosity of heavy oil and improve the recovery. Oil and carbon dioxide miscibility is controlled by pressure, temperature and oil composition. The capillary pressure forces which hold the oil immobile will disappear when carbon dioxide is injected.

1.3- CONVENTIONAL WATER FLOOD

Most of improved oil recovery processes involve injection of fluids (liquids, gas or chemicals). Water flooding however, is the most commonly used in improved oil recovery methods.

Waterflood is the oldest assistant and the most common oil recovery process. It was practiced as early as 1940s and 1950s. The full understanding of waterflood come form extensive research development efforts by companies and universities combined with field experience in 1960 and 1970s.

In addition to the enhanced oil recovery objective of water flood, water injection may by used to maintain the reservoir pressure when the expansion of gas cap and aquifer drive are not sufficient for this purpose. Selection of water injection as an enhanced oil recovery method is made according to both technical and economic criteria. If more than one method is technically good an economic analysis is carried out to select the method that optimizes the cost and the recovery. Water is the most suitable fluid for reservoir containing highly undersaturated oil. Moreover, water injection is more suitable in reservoir with saturated oil as long as the permeability is sufficiently high. Finally, water injection is more efficient in heterogeneous water-wet reservoirs.

1.4- GEL INJECTION

It has been observed that some of the injected fluids, gases and chemicals are directed toward a high permeability zone resulting in a poor sweep efficiency. This problem is commonly seen in the heterogeneous reservoirs The last proposed solution for this problem is to inject a polymer gel into the high permeability zone to direct the injected water to the unwept zones.

However, several earlier solutions have been proposed to solve this problem, such solutions are, injection of cement slurry, particulate solids, silica

gels, monomers that polymerize in situ and water soluble polymer. Although water shutoff treatments by cement were widely practiced, the successful rate have been lower than desired. Initially , the successful cement squeez will break down within months of the treatments necessitating additional cement squeezes to maintain shutoff. Moreover, cement left in the hole is more difficult to remove and will require a contamination and circulating out procedures or milling and under-reaming.

However, polymer gel systems have two main advantages over the cement. The polymer gel system is injected as a solution resulting in deeper penetration and will reduce the permeability in near wellbore area and plug the perforation. The polymer gel system solution can move up and down in outside wellbore sealing cracks and existing microannuli within the original cement sheath. Gel left in the hole can be cleaned out by using coiled tubing with either a mild acid solution or water. Polymer gel is less expensive than cement because of reduced crew and rig time. The gel properties are not affected by small errors in chemical concentrations. Finally, the polymer gel system behaves friendly with the environment.

Excess water production is related to two major causes which are water channeling from high permeability streaks or channels during waterflooding operations, and water conning. Water conning is a common problem encountered

when a reservoir is produced by bottom water-drive mechanism. Fractures and high permeability streaks are common causes of premature water breakthrough during waterfloods. For this reason gel treatments is used to reduce the flow through fractures and divert the injection fluids into hydrocarbons-bearing strata.

Polyacrylamide chromium (III) is one of the gel systems used in well and matrix treatments. Successful placement of a gel in specific location within the reservoir will depend on the ability to predict and to modify the gelation time of polyacrylamide chromium (III) gel. The stability and the rate of gelation will depend on several factors such as polymer types, polymer and cross linker concentrations, salinity, temperature and pH.

At high temperature reservoirs gelation time is reduced, and this reduction increases as the temperature increases[2]. In oil and gas wells the temperature increases as the depth increases. This limits the ability of placing the gel in the desired location. Gel solution may turn to solid like material under the effect of high temperature before it reaches the target location leading to an operation failure by plugging the well tubing. Sodium lactate as a retarder is employed to increase the gelation time at high temperature. Several experiments were conducted to determine its effectiveness in delaying the gelation time at high temperatures.

First, bottle testing experiments were carried out at various temperatures at different level of polyacrylamide, chromium acetate and sodium lactate concentrations. Then, the appropriate concentrations of these chemicals were selected. Next, several experiments were conducted to measure the viscosity of pre-gel solution. These viscosities could be used as guidelines to estimate the pumping time required for field operations. Finally, coreflood experiments were carried out to evaluate gel effectiveness in plugging the cores.

The objective of this thesis therefore, is to study the effect of retarder on the stability and gelation time of polyacrylamide chromium (III) gel system, and test its effectiveness as a plugging agent in porous media at high temperatures.

CHAPTER 2

CHAPTER 2

LITERATURE SURVEY

Polymer gels Attracted attention (in the early 1980s) as a technique to improve sweep efficiency in heterogeneous reservoirs, that have permeability variation, and to solve water conning problems. High permeability zone can prevent injected water from reaching the target locations resulting in decreasing sweep efficiency. Another source of low sweep efficiency waterflood is fractured formation

Several studies have been carried out to evaluate the advantages of using polyacrylamide chromium (III) gels in solving this problem. These studies showed the importance of several factors that are controlling gelation time and gel stability.

In 1981, **Terry, et. al**[1] studied the relationship between Polymer type and concentration, chromate concentration and reducing-agent type and concentration. They used five different types of polyacrylamide polymers and one polyacrylamide that was hydrolyzed to different degrees. The reducing-agent used was an anionic copolymer, cation copolymer, sodium bisulfite and thiouria.

They found that for a constant concentration of the metal ion-reducing agent, the reciprocal of the gelation time varies linearly with the reciprocal of the initial polymer concentration. Also, their result showed that as gelation time increased as the polymer concentration decreases for a given metal ion concentration, and as metal ion concentration decreases for a given polymer concentration. As the degree of hydrolysis of the polymer increases, the gelation time becomes more sensitive to the change in the polymer concentration. Finally, they found that a range of gelation time from a few minutes to a month can be obtained.

Also in 1981, **Jordan, et. al**[2] tried to generate data from on experimental work which involved the effect of temperature on gelation time for certain polyacrylamide Cr(III) gels. The temperature was varied from 25 °C to 80 °C. Moreover, dipolymers metal ion concentrations were varied. Five different materials were used in their experimental work. The materials included polymer with nonionic, anionic and cationic character. The result showed that the gelation time of polyacrylamide - Cr(III) decreased with increasing temperature. A linear relationship was found between the logarithm of the gel time and the reciprocal of the absolute reaction temperature. Also the gelation time was found to be a function of salt concentration.

Huwang Chyi-Gong. et. al.[3] in 1986 carried out an experimental study of the in-situe gelation of polyacrylonide Cr(III) in porous media. They injected the solution into 1-ft unconsolidated sandbacks. The nature of gelation in porous media is interpreted by using the pressure distribution along the flow-direction. It was noticed that the gelation occured much earlier than that occured in beaker tests where the gel solutions were maintained under static conditions. As a result of this, the shear was considered to be a major factor affecting the in-situ gelation rate. The shear history was found to be a factor that affected the gelation time by exposing the polymer gel solution to sand particles. It was found that a little effect on gelation time compared to the effect of shear rate.

In 1988, **Sydansk, R. D.**[4] conducted laboratory study to evaluate a new conformance-improvement-treatment technology of the polyacrylamide chromium (III) gel. These studies showed that gelation rate depends on polymer type and its molecular weight and the hydrolysis level. Polymer to chromium ratio, pH, salinity and temperature were also factors that affect gelation rate. It was concluded that the gel strength is increased with increasing Cr content. The chromium gel degraded to a low viscosity solution by contacting it with sodium hypochorate and hydrogen peroxide. The gel was stable at 124 °C.

The gel of his study can be formulated over a wide range of temperature, water salinities, polymer pH and contacting minerologies. Finally, he concluded

that the new gel technology that he studied is operationally and environmentally attractive.

Also, in 1988, **Purkaple, J.D.** and **Summers, L.E.**[5] described a testing procedure to identify the polymer gel systems for a particular field application. They used beaker tests to screen gel system, then coreflooding was employed for final system selection. Evaluation of 15 samples of polyacrylamide chromium (III) by beaker tests showed that low levels of polymer hydrolysis were required to produce consistent gels at reservoir condition. Flooding a core with two polymers from different polymer supplyers showed that both systems were capable of producing significant levels of permeability reduction for 50 days at reservoir temperature. At certain pressure gradient the first polymer began to degrade. They concluded that the limitation of using gels in oil field applications can be solved by controlling pH of the systems in the reservoir within a narrow range.

In 1989, **Moradi-Araghi,A. et. al.**[6] described stable, high temperature, and high salinity gels mixed with Cr (III) crosslinkers, using two stable polyacrylamides. It was observed that crosslinking, neither increased nor decreased the stability of the polymer. When Cr(III) was used with polyacrylamide, a stable gel was produced that survived one year of aging at 104 °C. A similar gel made with polyacrylomide began to synerese within a month and shrank more than 80%

in less than three months of aging at 93 °C. It was concluded that for obtaining a stable gel, a stable parent polymer is required to be used.

Also **Marty, L. et. al.**[7], in 1989, carried out an experimental work to obtain data on the effect of the flow rate on the gelation of polyacrylamide chromium (VI) that can be reduced to chromium (III) at a relatively low rate by Thiourea (reducing agent). Injection of polyacrylamide Cr (III) gels in unconsolidated sandbacks characterized by an abrupt increase in the apparent viscosity over a small section of the sandpack. The plugged zone was observed at a short distance in the sandpack. The location of this plugged zone was a function of the flow rate and its distance from the inlet, it increased as flow rate increased. They related this behavior to the filtration of gel aggregates. The data indicated that the gelation time decreased with increasing flow-rate and both shear rate and the age of the gel solution affected gel formation location in the plugged zone.

Also, in 1990, **Sydansk, R. D.**[8] conducted a laboratory study using Acrylomide Chromium (III) - Carboxylate gels. He concluded that the gels can be applied to reservoirs having hostile conditions with high salinity and elevated temperature. He studied the effect of concentration, molecular weight and hydrolysis-level of polymer, crosslinker concentration, temperature and salinity. He developed two versions of matrix treatments for near welbore, one is for low temperature application and the second is for high temperature application. The

result obtained from his study determined that the gels were stable at high temperature, and that pre gel solutions can be injected into a reservoir core over at least a temperature range of 22 °C to 124 °C and the gels consistently promote permeability reductions of an order of 10^{-3} to 10^{-6}.

Todd, B. J. et. al.[9] in 1990 presented a new numerical model based on the filtration hypothesis. This model was designed using polyacrylamide chromium (III). They believed that permeability decreased in the plugged zone because polymer molecules and pre-gel clusters are removed from the gelling solution by depth filtration. The filtration rate increases with aggregate size, polymer concentration and chromium (III) concentration. They observed that porosity and permeability decreased in the zone of rapid filtration, which formed a zone of high flow resistance. The results form this model indicated that for the system studied, the depth of gel placement is limited by the build-up of flow resistance which was found to be a linear function of flow velocity over the range investigated. They concluded that in the simulated runs there was no evidence of the shear effect.

Lockhart, T.P.[10], in 1991 described recent results of studies on Cr(III) crosslinked partially hydrolyzed polyacrylamide (HPAAM) gels. He observed that Cr(III)/HPAAm crosslinks in a chemical reaction which include ligand exchange, involving exclusively soluble, molecular form of Cr(III) rather than colloidal Cr(III) trihydroxide. He found that acetate is a thermodynamically weaker ligand

for Cr(III) than the carboxylate in HPAAm. He compared kinetic data for the reaction of Cr(III) with HPAAm and with monomeric carboxylate ligands. A result of this comparison indicated that Cr(III) oligomers were not involved in the gelation reaction under the normal conditions. He suggested that the gels prepared from chromium acetate complexes above pH 7 are kinetically rather than thermodynamically stable.

In 1992, **Seright, R. S.**[11] carried out an experimental work to investigate the effect of permeability and lithology on the performance of several gels, including the forms from Cr^{+3} (acetate)-Polyacrylamide. In this study a strong attention was devoted toward the effect of pH and fluid velocity in gel performance. The result showed that strong gel reduced the permeability while weaker gel was found to be occupying only small fraction of the pore space in the core. Also, it was found that the velocity coefficient increased with increasing the permeability.

Moreover, **Lockhart, T.P.** and **Albonica, Paola**[12], in 1992, introduced a new gelation technology for in depth placement of polyacrylomide Cr(III). In this new technology the malonate complex of Cr(III) was used to delay the gelation time. This new complex provided gelation delay at elevated temperature greater than that obtained from inorganic Cr or Cr(acetate). It was observed that addition of uncomplexed malonate provided further delays in gelation time. They investigated the dependence of gelation time on temperature. Cr(III) and malonate

ion concentration and pH. It was found that the decomposition of malonate which is a delaying ligand played an important role in determining the rate of gelation. They concluded that as the pH decreased, the decomposition of the retarding malonate is accelerated. They recommend that a constant pH should be used for the development of further control of gelation reaction and for prediction of gelation time within the reservoir.

They found that when the retarder is added to the solution of polymer (HE 100) and crosslinker in a solution of synthetic sea water it will give a gelation time range greater than that of fresh water solution at constant temperature. At 120° C the range of gelation time measured in synthetic sea water solution was between 0.25 and 42 hours while in fresh water solution the gelation time was between 1.2 and 33 days. Finally, it was found that the gel displayed excellent stability even at 120° C in synthetic sea water.

In 1992, also, **H. Sun, J. Liang** and **Seright, R.S.**[13] examined how gel types affect water and oil permeabilities in Berea sandstone. For this purpose they investigated the impact of wettability on the reduction of oil and water permeabilities. Moreover, they examined whether hysteresis of end points of oil and water permeabilities occured during the "pump-in, pump-out" sequence used during gel treatments.

Cr(III) $(acetate)_3$ polyacrylamide was one type that they used in their investigation. Three different formulations depending on the concentration of each element of this type were examined. They found that the flow of brine in porous media exhibited a strong apparent shear-thinning. Moreover they found that the fraction of original pore volume that remained open for oil flow was the same as that remained for water. The residual resistance factor for oil was less than that for water.

Albonico, Paola. Et. Al[14], in 1993, tried to determine the maximum gelation delaying potential for several retarding ligands. They carried out an experimental work to clarify the factors such as temperature, salinity, the addition of uncomplexed delying agent and hydrolyzed polymer that influenced the rate of gelation. In this study several powerful retarding ligands such as malonate and glycolate compared to acetate ligand were found. Also, it was found that the gelation time is sensitive to the concentration of the ligand in solutions, and adding of uncomplexed retarding ligand to the complex polymer solution will cause further increase in the gelation time. The gelation time resulted in this study ranged from several hours to more than 7 months.

In 1994, **Seright, R. S.**[15] examined several factors such as gelant viscosity, degree of gelation, and gravity that may have an important effect on gelant placement in a fractured system. The result showed that injection of pre-formed

gels improve sweep efficiency much more effectively than injection of gelants that formed gels in-situ. It was found that the viscous forces dominated over gravity forces during injection of aqueous gelants into fractured wells. Finally, the study concluded that there is still a need for more work to establish the best conditions for gels propagation in fractures.

Also, in 1994, **Southwell, G.P.** and **Posey, S. M.**[16] presented applications and results of Acrylamide Chromium (III) Carboxylate gels in well treatments in different fields. The results showed that the gels have proven to be cost effective by means of increasing the reserve up to 5 MMB. Also, it was found that using gel in treatments of production wells will increase the life of the field, and the gels proved to be successful in performing shut-off treatments where conventional cement would not be adequate.

Moreover, in 1994, **Bartosek, et. al.**[17] studied the effect of several variables like pH, temperature and the concentration of the retarding ligand on Cr(III) retention and stability of Cr(III)complexes. The result showed that the Cr(III) precipitation and retention in porous media were closely related phenomena, increasing pH and temperature will increase the tendency of Cr(III) complexes to undergo hydrolysis and precipitation.

Moreover they found that addition of sodium malonate or glycolate ligand improve Cr(III) acetate propagation and prevent it form sharply degrading. Finally,

it was found that Cr(III) precipitation is chemically reversible reaction. This precipitate can react with subsequently injected polymer causing a rise in injection and accelerated gelation.

Also, in 1994, **Liang, Jenn-Tai. eT. al.**[18] tried to find out why gels reduce water permeability more than oil permeability. The authers examined several factors such as gravity effects, lubrication effects, gel swelling and shrinking, water and oil pathway constructions, wettability effects and segregated water and oil pathways. Four types of gels including Cr(III)-acetate - HPAM were used in this study. The results of the experiments showed that gravity effects, lubrication effects, gel shrinking and swelling were not responsible for the permeability reduction. Moreover, the results indicated that wettability may influence the permeability reduction but it appeared that it was not the root cause for this phenomenon. The results obtained with oil-based gel suggests that separation of oil and water pathways through a porous medium may play the dominant role of this phenomenon. Finally, the authers recommended that additional work is required to verify this concept.

Also, in 1994, **Naser-El-Din, H.A.**[19] conducted an experimental study to investigate the effect of gel type, gelant concentrations, salinity, hardness, and temperature on gelation time for several systems of gels including polyacrylomide Cr(III). It was found that polyacrylamide Cr(III) does not need low salinity

preflush and it can be prepared in saline water. By using this gel the permeability was reduced by more than 95%. This gel has an excellent mechanical properties, minimum syneresis and good long term stability.

Moreover, in 1994, **Lockhort, T.P. et. al.**[20] introduced a new simple chemical approach to control the gelation reaction of Cr(III) polymer solutions that meets the gelation delay requirements for in-depth treatments of high temperature reservoir. The authers pointed out that introducing Cr(III) as a complex Cr(malonate) will prolong the gelation time in order of magnitude, compared to that obtained by either Cr(III) hydrated ion or Cr (acetate). Addition of uncomplexed malonate ion to Cr (malonate) will further increase the gelation time of Polyacrylamide Cr(III). This uncompelxed malonate ion found to be an important factor influencing the gelation delay. On the other hand, it was found that gelation time decreases with increasing pH when Cr(malonate) is used without malonate ion. However, the decomposition of malonate ion is accelerated at low pH.

In 1995, **Mohammed, M. A.** and **Al-Majed**, A. A.[21] carried out a statistical analysis (fractional design) in order to identify the influence of polymer type, the initial polymer and redox concentrations and temperature on the in-situ gelation process. The result obtained from the developed mathematical model indicated that initial polymer concentration, redox concentration and polymer type have

significant effect on gelation time. The authers found that for a given polymer type a polynomial form exists between the gelation time, initial polymer concentration and redox concentrations. The coefficient of this relation vary with polymer type. Finally, it was observed that the effect of temperature on gelation time appears as an inverse exponential relationship.

CHAPTER 3

CHAPTER 3

FACTORS AFFECTING GELATION TIME AND STABILITY OF GELS.

3.1- DEFINITION OF GELATION TIME

Gelation time has been defined as the time required for the solution to reach a certain viscosity[1]. More specifically gelation time has been defined in terms of the gelation point[2] which is defined as " the point of maximum rate of increase of viscosity ", " the point at which the viscosity becomes infinity " and as " a point on the steeply rising part of the viscosity Vs. time curve ". Moreover, gelation time has been defined as " a reading of 5 on LVT model at shear rate of 12 rpm ", " a reading of 10 on RVT model at a shear rate of 20 rpm ", and as " a reading of 25 on 100-devision scale ". The reading in the above three definitions corresponds to 500 cp on brookfield viscometer.

3.2- FACTORS AFFECTING GELATION TIME

The factors that affect the gelation time are listed below.

1- Polymer and redox concentrations

2- The reducing agent

3- The temperature

4- The shear rate

5- The molecular weight of the polymer

6- Polymer hydrolysis

7- Solution pH

8- The salinity

9- The flow rate

10- The oxygen on the top of the vial

11- Organic ligand type

The above factors are discussed below

3.2.1- Effect Of Polymer And Redox Concentration

From Kinetic theory, the time required to achieve a given extent of reaction decrease with increasing initial reactant concentration. A study [1] was carried out to see the effect of polymer concentration and redox concentration on

the gelation time of polyacrylamide gel system. Results from this study indicated that the gelation time decreased as the initial polymer concentration increased while holding the redox concentration constant. Moreover, gelation time increased as the initial redox concentration decreased while holding the initial polymer concentration constant.

3.2.2- Effect Of Reducing Agent

A reducing agent is a chemical substance that is used to reduce Cr^{+6} to Cr^{+3} . The reducing agents that will give longer gelation time are preferable when using gel for field application because the reducing agents that will give shorter gelation time will have limitation in their application. Thiourea and sodium bisulfite were used as reducing agents. It has been found that the gelation time obtained from thiourea was 50 to 70 times longer than that obtained by using sodium bisulfite. This is because sodium bisulfite reacts faster than thiourea. Chosing a proper reducing agent is a major step that is required fo control the gelation time for field application [1].

3.2.3- Effect Of Temperature

According to Arrhenius equation given below, many homogeneous chemical reactions are affected by temperature

$$d (Ln\ k) / d (1/T) = - Q / R$$

Where Q is the energy of activation (cal / g mol)

k is specific rate [min^{-1} ($g/m^3)^{1-n}$]

T is the absolute temperature (K)

R is ideal gas constant 1.986 (cal / g mol K)

Experiments were carried out to see the effect of temperature on gelation time. The range of the temperatures used in these experiments is from 25 ° C to 80 ° C. The results of these experiments indicated that the gelation time decreased with increasing temperature. A linear relationship between the logarithm of the gelation time and the reciprocal of the temperature were found [2].

3.2.4- Effect Of Shear

The effect of shear on the rate of gelation was investigated [3] by flowing the polymer solution in tubes of 0.078 inch ID and length of 311 inches. The

linear velocity was 0.005 in / sec and the shear rate at the wall was estimated to be 0.5 sec^{-1}. The effluents from tubing were collected at different batches and stored at 25 ° C. The viscosity of the samples then was measured at deferent times. The results indicated that the imposed shear rate shortened gel time and the effect depended on the shear history of the samples, i.e, the earlier the shear rate the shorter the gelation time.

The effect of shear rate on the location of the gel point in a coreflood has been studied by Marty et. al [7]. The location of the gel point can be inferred by estimating the age of the gel aggregates that are retained at the gel point. Experiment carried out at frontal velocity of 1 ft/ day showed that the gel aggregates captured at the gel point of approximately 20 hours. At frontal velocity of 2.5 ft / day the gel aggregates captured at gel point of approximately 35 hours. If the age of the gel is the only factor for initiating the gelation, the gel of 20 hours gelation time should be captured at 2.1 ft from the inlet at 2.5 ft / day frontal velocity. However, the gel at frontal velocity of 2.5 ft / day was captured at 3.65 ft from the inlet. From this study, it proved that the gelation time is delayed if the frontal velocity increased in-situ. This effect is related to the increase of shear rate. A plugged zone is formed and its distance from the entrance increased as the flow rate increased.

The effect of shear rate on in-situ gelation was investigated by examining the effect of grain size at fixed shear rate. The gelation time was 240 minutes compared to 400 minutes for the same system in a beaker. The gelation rate was accelerated with increasing shear rate, but keeping the shear rate constant, the sand particles size had very little effect on the insitu gelation times.[3].

3.2.5 Effect Of Molecular Weight

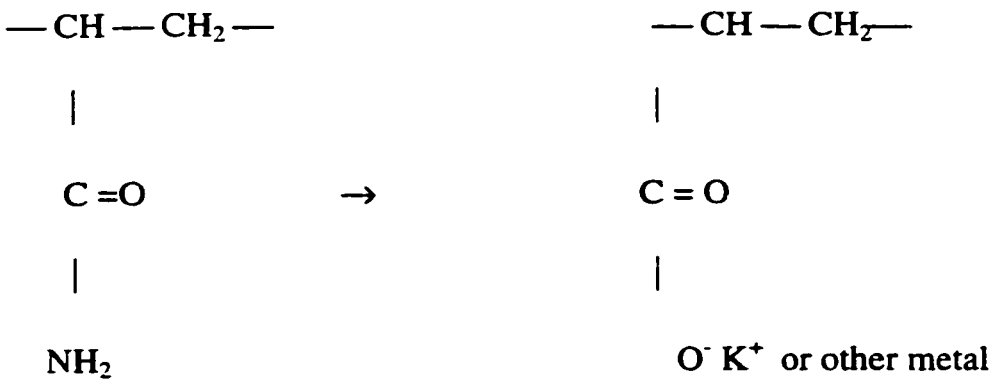
The effect of molecular weight on gelation time was studied by Purkaple and Summers [5]. Two types of polymers with high (Havis 350) and high to medium (Pusher 1000) molecular weight have been used in their study. The high molecular weight polymer gave shorter gelation time than pusher 1000 which is classified as medium to high molecular weight polymer. This is because the number of crosslinkers required for gelation is inversely proportional to the weight average molecular weight. This is true only when both polymers are at the same hydrolysis level, pH and salinity. The effect of molecular weight can be reversed depending on the hydrolysis level. A lower molecular weight polymer with a low hydrolysis levels has faster gelation time and higher gel strength than a higher molecular weight polymer if tested at the same pH and salinity.[8].

In general as Polyacrylamide molecular weight increases at constant polyacrylamide concentration and hydrolysis, the gelation rate increases and the gelation time decreases. The polyacrylamide viscosity in this case will increase. However as the molecular weight decreases, the required concentration of polyacrylamide increases to formulate an acceptable gel strength [8].

The hydrodynamic size of the molecule of gel solution increases with time as the gelation process occurs. The increase in the molecule size follow the same trend as the viscosity. The viscosity increases slowly for a long period of time and increases sharply in the last few hours of the gelation process [6].

3.2.6- Effect Of Hydrolysis

Hydrolysis is the conversion of carboxamide group to carboxyl group as shown below[1]



In general gelation rate increases with increasing hydrolysis level. The crosslinking of polyacrylamide occurs through the polymer pendent hydrolyzed carboxylate group and not through the pendent. amide group which are the only groups existing in the completly unhydrolyzed polyacrylamide. [8].

3.2.7- Effect Of pH

Lockhart [10] found that for Cr^{+3} / HPAAM gels prepared from inorganic Cr^{+3} ions, the pH had an effect on the gelation reaction. Experiments carried out at pH ranges of 2.3 to 10.4 to investigate the behavior of gel solution prepared from mixing 50 ppm Cr^{+3} and 8000 ppm polyacrylamide of 0.70% hydrolysis at initial pH $\leq$ 6.6, indicated that gelation occurs where Cr^{+3} is present exclusively in soluble molecular forms (pH $\leq$ 5.3). This proved that crosslinking by molecular form is possible. However, polymer solution remained fluid during the experiment where Cr^{+3} is converted quantitatively to

insoluble, colloidal Cr^{+3}. This indicated that colloidal Cr^{+3} is inactive toward polymer crosslinking (at least above pH 7). Cr^{+3} ions prepared from chromium acetate as high as pH 9 is kinetically stable and has different gelation mechanism from that of inorganic Cr^{+3} ion [10]..

Purkaple and Summers [5] tested the effect of pH in-situ by carrying out corefloods experemints using different polymer types of different molecular weights. They concluded that it was not practical to control the pH in the field applications. Although the gel solution pH could be adjusted in the field, the accuracy of pH control may be reduced significantly when adjusting large batches of polymer solutions. Moreover, the large buffering capacity of the rock in the reservoir would limit the efforts to control the pH at the surface. Based on this reasoning formulations close to the pH of the produced water were thought to be the most attractive for field use [5]..

3.2.8- Effect Of Salinity

The effect of varying sodium chloride concentration at 25 ^{o} C on the gelation time of polyacrylamide chromium (III) system was investigated.by Jordan et. al [2] . When the sodium chloride concentration was varied between 5000 and 10000 g/ m3, the effect of salinity was qualitatively the same for all systems measured but was more marked for the systems with lower polymer concentration. The gelation time is a function of Na Cl concentration. The time decreases slightly with increasinng salt concentration upto approximately 5000 - 10,000 g / m^3 and then increases as salt concentration increased. The viscosity of

a polymer solution decreases as the salinity is raised from 0 to 10000 g/m3 sodium chloride. The decrease in gelation time may be related to this viscosity change [2].

Screening experiment to evaluate the effect of salinity on several polymer types were made by Purkaple and Summesrs [5] The polymers had similar hydrolysis level (19 %), but differed in molecular weights. The salinity of the mix water was varied from fresh water to seawater spanning a wide range of salinity usually available in the field. The reaction temperature varied from 71.1 ° C to 82.2 ° C . The results indicated that the seawater formulations had faster gelation time and lower gel strengths than the freshwater. [5].

3.2.9- Effect Of Flow Rate

In most models of flow in porous media, the in-situ shear rate is proportional to the frontal advance rate. Coreflood were carried out by Marty et. al [7] to determine the effect of flow rate on gelation time. The gel was injected into a sandpack and the gelation time was monitored. It was found that the gelation time was shortened during flooding experiments indicating that the gel reaction is faster than that of a bulk test , i.e, the gel solution was prepared in a beaker under low shear. At frontal velocity of 1 ft/ day and 2.5 ft/ day the

gelation time was 66 hours and 52 hours respectively compared to 72 hours for a bulk gel [7].

3.2.10- Effect Of Oxygen

Oxygen present at the top of the gel solution as a cap affect both the formation of gel as well as the rate of gelation. This oxygen will decrease the viscosity or the molecular weight of the polymer at elevated temperature. The oxygen of the water dissolved in the polymer however does not appear to severely affect the gelation time of the polymer [6]

3.2.11- Effect Of Organic Ligand Types

Several organic ligands delaying additives were examined by Albonico et. al[14] to evaluate the effect of each one on gelation time of polyacrylamide gels. These ligands are acetate, 2-hydroxy butyrate, serine, 2-aminobutyrate, lactate, glycolate, slicylate, malonate, ascorbate and oxalate. It was found that the strongest ligands was ascorbate which gave a gelation time of 51 relative to acetate. Malonate gave gelation time of 33, salicylate 27, glycolate 12, and lactate 9. The experiments were carried out at 120 ° C.

Moreover, it was found that the gelation time increased with increasing the concentration of uncomplexed ligands. However, the most powerful gelation

delaying composition in all conditions were those based on malonate complex with the addition of uncomplexed malonate [14].

3.3- LIGAND EXCHANGE CHEMISTRY OF Cr^{+3}/ POLYACRYLAMIDE CROSSLINKING COMPLEX

Ligand exchange refers to the substitution of ligand bonded to a metal ion for other ligand in the solution. The position of exchange depends on the relative stabilities at the relevant metal ion / ligand complexes. The ligand exchange is shown in the following equation [12].

$$Cr^{+3}(HPAAm)_n + mL \quad \leftrightarrow \quad Cr^{+3}(L)_m + n\,HPAAm$$

Gel crosslinking Degelation solution

However, the major unknown is the strength of the ligand that will displace the equilibrium to the right in the equation. Moreover, the rate of gelation and degelation in the crosslinking gel matrix is also unknown [12].

3.4 - Gel Strength

Sydansk[4] noted that as compared to reological measurments, determination of gel strength via gel break down pressure in porous media or via gel yield pressures through an orifice is a better measure of gel strength for rigid gels. He used gel solution containing 2.2 % polyacrylamide in freshwater. The polyacrylamide to crosslinker ratio is 80 : 1. The gel initialy aged at 60 ° C has yield pressure in excess of 500 psi into 1.5 mm diameter orifice tubing of 0.3m length. The tubing was filled with gel. At 124 ° C the gel did not flow for five days [4].

Moradi - Aagh et. al [6] used the percent gel strength (% G S) defined below:

$$\% \text{ G S} = (22.5 - \text{T L}) * (100 / 22.5)$$

where T L is the tongue length of gel in an ampules placed horizontaly after aging in the vertical position. (22.5 cm is th length of glass ampules)

3.5 - GEL STABILITY

Sydansk [4] demonstrated the long term thermostability of gel using bottle testing procedure. Prior to sealing the ampules, Oxygen removal can be done by

vacuum degassing. The ratio of polymer to cross linker in his experiment was 88 : 1. The gel remained stable for 1.7 years to the date of observation. The temperature ranges used were from 22 ° C to 124 ° C [4].

Phase stability at room and reservoir temperatures was studied by Sydansk also. Phase stability is measured by noting the amount of gel swelling or shrinking with time. The results indicated that gels were relatively quite phase stable with time and little gel swelling or shrinking was noted [4].

Gel can be degraded back to a low viscosity solution by connecting it with a solution containing chemicals such as sodium hypochlorite, hydrogen peroxide or other peroxo compounds. This degredation has been demonstrated both in field and laboratory studies. The severity of the degredation depends on whether the gel has been effectively contacted by degrading chemical solution [4].

Using thermally stable polymer gives a stable gel. The stablility of the polymer can be maintained if the hydrolysis of the amide group in the polymer is limited by copolymerization with other monomer. The stability of the parent polymer therefore will determine wether the produced gel will be stable or not. [6].

Sydansk [8] studied the stability of the gels by adding saline water. Using bottle testing , a gel solution, containing 2.0 % polymer and with polymer to crosslinker ratio of 88 : 1 in fresh water, was found to be stable for 3.6 years at 124 ° C. Addition of synthetic sea water reduced the stability of the gel to 2.5

years at temperature ranged of 85 ° C to 124 ° C. This gel was tested by adding North sea produced formation brine which has a total solid of 120000 ppm. The gel, aged at 124 ° C, remained stable and rigid after 120 days [8].

Albonico et. al [14] reported that several factors affected the stability of gels. These factors are the presence of air in the samples and polymer hydrolysis which is rapid at 90 ° C and above. The presence of air in gel solution leads to degredation of gel molecules and degelation of the formed freshwater gel at elevated temperature. However, polymer hydrolysis led eventually to extensive syneresis of synthetic seawater gels [14].

Therefore, these factors should be avoided or the effect of them should be minimized. The presence of air can be reduced from gel solution. The polymer that has high resistance to hydrolysis should be chosen. A study carried out with different ligands, revealed that the stability of the gels depended on the type and concentration of the delaying ligands present [14].

Several organic ligands such as acetate, lactate, malonate, glycolate and salicylate were used to study the effect of each one on the stability of gels. For glycolate, the stability of synthetic seawater decreases as the glycolate concentration increased. The resistance of malonate gels in synthetic seawater

however increased with increasing malonate concentration. Moreover the presence of additional retarding ligands in uncomplexed form in gel solution will further stabilize Cr^{+3} ion in complexed form displacing the equilibrium to the left in the following equation [14].

$$Cr(L)_n + m\ P\text{-}CO_2 \leftrightarrow Cr(PCO_2)_m(L)_{n-m} + m\text{-}n\ L$$

Crosslinking complex

Where $m \geq 2$

Several experiments were carried out by Bartosek et. al [17] to evaluate the stability of polyacrylamide chromium (III) gel system using acetate, glycolate and malonate complexed ligands. These experiments were carried out to study the stability of the gels at elevated temperature in bulk synthetic seawater. The initial pH for the these experiments was 6. The solution was heated at 90 ° C and 120 ° C and the extent of Cr(III) hydrolysis and phase separation was observed by visual inspection at different times [17].

Under these conditions the Cr(III) acetate and glycolate complexes underwent comparable extensive and rapid phase separation, while the Cr(III) malonate proved to be more resistant to hydrolysis. The pH evolved differently

during the experiment. The pH of Cr(III) acetate has dropped to 4 after 15 minutes of heating. However the pH of glycolate and malonate stabilized at 6-6.1 and 5-5.3 respectively. This result proved that the Cr(III) acetate complex is unstable to hydrolysis even at pH = 4 at 90 ° C [17].

Other experiments were carried out with Cr(III) and malonate complexes in order to quantify the precipitation of Cr (III) as a function of temperature, pH, and delaying ligand. In these experiments quartz and sand were added because they have an effect on gel propagation. The result indicated that the Cr(III) was lost rapidly from Cr(III) acetate solution(200 ppm) at 90 ° C, and less than 20 ppm was remaining in the solution after 1 day. The pH of Cr(III) acetate solution initially was 5, stabilized at 4.5 at 60 °
C and 4.3 at 90 ° C within the first few hours of these experiments. These experiments supported the conclusion that the upper pH at which Cr(III) acetate is stable to hydrolysis diminishes sharply with increasing temperature [17].

The Cr(III) malonate complex displayed markedly better stability to precipitation at 90 ° C than Cr(III) acetate at 60 ° C. The result indicated that the solubility of Cr(III) malonate was improved in the presence of additional uncomplexed malonate. The result proved also that the use of stronger ligands for Cr(III) and higher ligand concentrations improved the solubility of Cr(III) in solution at elevated temperature [17].

3.6- IN-SITU GELATION

The in-situ gelation experiments conducted by Huang et. al [3] is summarized here. They used the system shown in table 1. The sandpack was prepared from Ottawa sand. The sandpack was divided into 7 sections as shown in table 2. The porosity of the sandpack was 35.5 % and the permeability was 6.1 darcies [3].

Table 1 — Composition of gel system

Gel System	Water cut 160 (ppm)	Sodium dichrmate (ppm)	Thiourea (ppm)	Sodium Chloride (%)
	4210	383	382	1.68

Table 2 — Sections of the sandpack			
Section	Length (cm)	Starting) cm)	Ending (cm)
A (entrance)	1.3	0	1.3
B	5.1	1.3	6.4
C	5.0	6.4	11.4
D	5.1	11.4	16.5
E	5.1	16.5	21.6
F	7.6	21.6	29.2
G (exit)	1.3	29.2	30.5

Injection of gel solution began 30 minutes after the solution was prepared. The frontal Flow rate was 2.05 ft/ day which is equivalent to a volumetric flow rate of 10.5 ml / hr. Effluent samples were collected in discrete fractions over time period of 30 minutes. As the samples were collected, they were moved to a 25 ° C water path for later analysis of pH, polymer concentration, Cr^{+3} concentration and viscosity. The pressure drop exceeded the full scale of the

pressure transducer after 93 hours and hence the apparent viscosity was not available after that time [3].

The initial increase in the viscosity (up to 14 hours) is proportional to the elapsed time. This is a direct result of displacing the resident brine with more viscous gel solution. After the gel solution broke through at the outlet, the apparent viscosity was constant at about 22cp for a period of time. It started increasing after 60 hours and increased sharply after 85 hours. The apparent gel time was assumed to be 85 hours. The gelation time for this system in a beaker is 240 hours. This indicated that the gelation time occurred much earlier in the porous media than in the beaker. By observing the gel time in each section, it appears that there is an inverse relationship between gelation time and distance from the inlet. The polymer concentration from subsequent effluent gradually declined, indicating entrapment [3].

3.7- EFFECT OF GEL ON PERMEABILITY

Todd and Willhite [9] proposed a model for in-situ gelation. The permeability in the plugged zone decreases because of the filtration of polymer molecules and pre-gel clusters with depth. When the polymer was injected into the porous media, a layer of polymer was adsorbed onto the surface of the sand

grain by physical entrapment and surface attraction. This layer had little effect on permeability. However. when the crosslinking started and the pre-gel cluster developed, some cluster collided with the porous media and then became attached to the previously deposited polymer [9].

As the attached polymer and crosslinker increased, the porosity and permeability decreased gradually in the zone of rapid filtration. Usually, the gelling solution is like a particle with diametr ranges from 0 to 5 microns. When the diameter of the gelling particle exceeds the pore throat diameter, the particles will be unable to pass through. These particles collide with the porous media and retained by crosslinking with previously deposited polymer. This will increase the flow resistance in region of high deposition leading to decrease in porosity and permeability [9].

Flooding data were generated from experiments carried out at temperature ranges from 85 ° C to 124 ° C. These experiments carried out using different core samples and pressure of 1000 psi. These core samples,sandstone, are real reservoir cores from Alaskan reservoir and from offshore Gulf Cost formation. These experiments indicated a permeability reduction of order of 1×10^{-2} to 1×10^{-6} (k_f / k_i) [8].

Other experiments carried out by Seright [11] in three types of rock including high permeability Berea Sandstone, low permeability Sandstone and Indiana limestone with porosity of 0.22, 0.19 and 0.19 respectively. It was found that the strongest gels reduced the permeability of all cores to approximately the same value. For weaker gels, the residual resistance factor ($F_{rrw} = k\ \mu^n$) decreased with increasing rock permeability in Berea Sandstone [11].

Liang and Seright[13] explored the reduction of oil and water permeabilities using gels. It is known that gels reduce water permeability more than oil permeability. However there is no rational explanation for the phenomenon. Four types of gels were examined to know how they can reduce water permeability more than oil permeability in Berea Sandstone. These gels are Cr(III)(chloride)-Xanthan, Cr(III)(acetate) polyacrylamide, resorcinol-formaldehyde and colloidal silica. Core floods were carried out for this purpose and found that all gels reduced permeability to water more than permeability to oil [13].

The colloidal silica gel however reduced the permeability to water and oil to about the same value. It was found that hesteresis of oil and water permeability were not responsible for the behavior observed during the studies. Finally, clear understanding of why some polymer gels reduce water permeability more than oil permeability is not found yet [13].

3.8- FACTORS AFFECTING THE DISPROPORTIONATE PERMEABILITY REDUCTION

Since the capacity of gel to reduce water permeability more than oil permeability is critical for the success of gel treatments, A study to see the enfluence of gravity effect, lubrication effect, gel swelling and shrinking effect, water and oil path ways constriction effect, wettability effect and segregation of water and oil path ways was carried out by Liand et. al [18].

3.8.1- Gravity Effect

Experiments carried out on cores oriented horizontally and vertically in order to test the effect of gravity on permeability reduction. The Glyoxal-CPAM gels with 0.3 % CPAM and 0.114 % glyoxal were used in these experiments. The water or oil first was injected into a core directed horizontally. The water and oil residual resistance (F_{rrw} and F_{rro}) were measured. Then the oil or water was inject to core directed vertically from top and bottom of the core. The result indicated that The F_{rrw} and F_{rro} were not sensitive to flow direction or core orientation. The gel however reduced water permeability more than oil permeability. These result suggested that the disproportionate permeability reduction was not caused by gravity effect [18].

3.8.2- Lubrication Effect

The concept of lubrication effect applied to strongly water wet cores. The polymer or gel adsorbed onto the wall of the core. The presence of the hydrocarbon / adsorbed polymer interface effectively lubricates the flow of oil or gas through the center of the pores. Based on this concept it was expected that the residual resistance factors vary with oil viscosity during core experiments with gels present [18].

Two types of oil A and B with viscosities of 1.05 cp and 31.6 cp respectively were used with strongly water wet Berea sandstone, to investigate the lubrication effect. After saturating the core with brine. oil A was injected to determine oil permeability at residual water saturation. Then oil A was displaced by oil B which finally was displaced by oil A, and the permeabilites for the both oils were measured. Next, brine was injected to determine water permeability at residual oil saturation. This procedure was repeated three times in two directions. The results showed that the effective permeabilities for both phases varied little. Therefore, there is no evidence of lubrication effect before placing the gel in the core [18].

Then six pore volume of Cr(III) acetate-HPAM gelant were injected into the core. The core was oilflooded with both oils and the residual resistance factors

were measured. The core was then waterflooded to determine the water residual resistance factors. The residual resistance factors for both oils were approximately the same indicating the absence of lubrication effect. However, the water permeability was reduced more than oil permeability. These result indicated that the disproportionate permeability reduction was not caused by

3.8.3- Gel Shrinking And Swelling

Gel swelling and shrinking were found by observing the change in gel volume. Cr(III)-acetate-HPAM gel and resorcinol-formaldehyde gels were observed at atmospheric pressure but there were no change in their volumes. No significant change in the volume was seen during multiple exposures of the gels to brine and compressed CO_2 [18].

For further investigation, coreflood experiments were carried out. Five pore volumes of Cr(III)-acetate-HPAM were injected. Then oil was injected and the residual resistance factors were measured at a back pressures of 0, 500, 1000, 1500 psi. The results of these experiments indicated that the residual resistance factors were not sensitive to the system pressure. During the experiments, the gel reduced water permeability more than oil permeability. However, gel shrinking and swelling were not responsible for disproportionate permeability reduction [18].

3.8.4- Effect of Water and Oil Pathway Constrictions and Wettability

The following equation was proposed by Zaitoun and Kohler to estimate the permeability reduction after polymer and gel treatments.

$$F_{rr} = [\, 1 - \delta / r \,]^{-4}$$

Where F_{rr} is the permeability reduction

δ is the thickness of polymer or gel absorbed on pore walls

r is the radius of the pore

According to this equation as the thickness increase or as the radius decreases the permeability reduction increases. Zaitoun and Kohler proposed that in strongly water wet formation if an oil droplets exist in the pore radius during waterflood, these droplets can effectively reduce the pore radius. However, this constriction does not exists during oilflood. According to the above reasoning, the polymer or gel will be absorbed to the walls of the pores in stronger water wet formation more than in weak water wet formation. Thus , the disproportionate permeability reduction should be weak in less and intermediate water wet formations [18].

Experiments were carried out on strongly and intermediate water wet cores using a resorcinol-formaldehyde gel and a Cr(III)-xanthane gel. For a resorcinol-formaldehyde gel, the permeability reduction in intermediate water-wet cores were more than in strongly water-wet cores. However, for Cr(III)-xanthan gel, the disproportionate permeability reduction was not evident. Therefore, the effect of wettability on the disproportionate permeability reduction was not the main cause [18].

3.8.5- Effect of Segregated Oil and Water Pathways

During high water cut experiments, water flows through most of the pores and forms water path ways while the remaining pores form oil path way.. As a result if a water based-gelant flows through the water pathways, the oil pathways remain connected and gel-free. Thus the water-based gel will reduce water permeability more than oil permeability. On the otherhand, if an oil-based gelant follows the oil pathways, the water pathways remain connected and gel-free. In this case the oil-based gel will reduce oil permeability more than water permeability [18].

Experiments carried out using an oil-based gel consisting of 12-hydroxystearic acid and oil of 1.05 cp viscosity. The result indicated that the number of oil pathways that remain open has been reduced. Thus the segregation of oil and water pathways through a porous medium may play the dominate role in causing the disproportionate permeability reduction [18].

3.9- FIELD APPLICATION

Southwell and Posy [16] reported the results of many well treatments. Reservoirs with water drive mechanism are more susceptibel to watered out zones, especially if oil is produced from these reservoirs with high production rate and water has high relative mobility. The watered out zone will be formed between the water drive and the production well.

Understanding the problems is the key to the success of gel treatments. Enough informations about the problems are needed to determinre the type of treatments that can be applied. Such as knowing from where water is coming, the severity of the problem, the geology of the zone to be treated, and the nature of well completion (i.e., open hole or cased hole). The cost of a workover and the current price of oil are important information that have to be known befor gel treatments. Shut-off treaments using polyacrylamide chromium gel can be applied in wells with abnormally rapid or large rise in water production.

Wells that are candidate to gel treatments should have some features that indicate the necessities of treatments by polymer gels. These features are wells that have high WOR which may be the result from high permeability bottom water zone or from water conning or wells That initialy had high oil production with no or little amount of water production. The high level of oil water contact in some wells could produce high amount of water, placement of the gel in the zone of water conning will shut-off or reduce the amount of water production. Finally wells that penetrate zones with high relative permeabilty to water and the oil water interface lies below the production zone will be candidats for gel treatments to reduce the water / oil ratio.

Gels have been used for areal conformance treatments. The injection of the gels increased the production of oil. The cost is approximatly less than $ 1.0 per stock tank barrel of oil. Moreover, water oil ratio was reduced by a factor of approximately 10. .

On the otherhand, gels can be used in near wellbore treatments. In this case gels were used as a substitute of squeeze cementing for total shut-off. This technology has been used to shut-off water or gas. Gel technology has been used to seal the open hole curved section of re-entries for horizontal wellbore completions.

[16].

CHAPTER 4

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1- MATERIAL and EQIUPMENTS

4.1.1- MATERIALS

4.1.1.1- Polyacrylamide

The polymer used in the experiments is commercial polyacrylamide (FLOPAAM 0331 L). The polyacrylamide is characterized by concentration of 15 % and hydrolysis of less than 1 mole %. The bulk viscosity of this polyacrylamide is 10000 cp and it has a molecular weight of 300,000 which is considerd as medium molecular wieght.

4.1.1.2- Chromium Acetate

Chromium acetate (X- LINK 5000) was used as crosslinker at different concentrations. It is a dark green solution. The concentration of chromium acetate is 11.5 % +/- 0.3 %. The percentage of chloride in the solution is 0.05 % and the

percentage of sulfate is 0.05 %. X- LINK 5000 is used in pigments, drilling muds,textile mordants, leather tanning, and as catalysts for oxidation, polymerization, and emulsion hardening.

4.1.1.3- Sodium Lactate

Sodium lactate (retarder) with different concentrations was added to the solution to delay the gelation time at high temperature. Sodium lactate solution is a clear, slightly viscous aqueous solution confining 60 % by wieght of sodium lactate The crystaline sodium salt of the lactic acid is very hygroscopic and extremely difficult to isolate. The commercial 60 % solution is both colorless and odorless while possessing a mild saline taste. It exhibits a strong antimicrobial and humectant properties in many foods, pharmaceutical, and cosmetic applications. It is also used in conjunction with lactatic acid in products designed to help rejuvenate aging skin. The percentage of water is 40 +/- 0.5 % and the percentage of sodium is 12.3 +/- 0.2 %. The concentrations of iron is less than 1.0 ppm and the heavy metals are less than 1.0 ppm. The specific gravity ranges from 1.31 to 1.34 and the pH ranges from 6.8 to 7.2.

4.1.2- EQUIPMENTS

The equipments used in the experiments are bottles or vials, Wells - Brookfield viscometer, ovens and Core flooding setup

4.2 - GEL EVALUATION TECHNIQUES

There are many techniques that are used to evaluate gel and are reported in the literature. These techniques include visual observation using Bottle testing (Beaker Test), which is a nondestructive technique. Another technique depends on the measurement of the viscosity at low shear which is a destructive technique and is not accurate due to slippage at the wall and it might accelerate the gelation time due to mixing [6] .

Rolling ball viscometer has also been used for determining the gel time. Gel could be evaluated through gel strength measurements. This can be carried out by measuring the force needed to move the gel which has been previously set in a glass tube. Dynamic oscillatory measurements which is a nondestructive technique has been used to evaluate gel. In this technique the complex viscosity is composed of a viscosity component or loss modulus and a storage modulus. A bulk gel strength tester measure the minimum amount of pressure under which gel is extruded through a 30 - mesh wire screen. Finally, pulse shearometry

technique has been used for this purpose. In this technique the gel is placed between two discs. Then a pulse wave is generated by the driving disc. This wave will propagate through the gel and will be detected by the sensing disc. This technique is the least disturbing method and does not affect the gelation process [6].

In this study the technique proposed by Sydansk [4] was followed. The gel strength code which he developed was found practical and convinient for bottle testing. Gel viscosity was measured using Wells - Brookfield viscometer. The viscosity range that can be calculated using this model is very wide.

4.2.1- GELATION TIME MEASUREMENT BY BOTTLE TESTING

4.2.1.1- GENERAL PROCEDURE

1. Polyacrylamide chromium (III) gel system samples were prepared by mixing appropriate concentrations of polymer, chromium acetate, destiled water in glass vials.
2. Samples were aged in forced air ovens which allow for minimum temperature variation.

3. The experiments were carried out at room temperature. 60 °C, 90 °C and 120 °C in order to see the effect of temperature on gelation time and stability of the gels.
4. Gelation time were determined by visual inspection of the sample tubes removed briefly from the oven/baths.
5. New samples were prepared after adding the retarder (sodium lactate) at different concentrations to the solution to determine its effect on gelation time and stability of the gels.
6. Repeat step 1 - 4

Bottle testing provides a semi-quantitative measurements of gel strength and gelation rate. By using bottle testing, the gels can be screened and formulated rapidly and inexpensively over a wide rang of gel formulations, brine compositions and temperatures. Since gels can not be removed or transferred to another container unless some of the gel network or crosslinking are broken, bottle testing is attractive for long-term-stability. Therefore, the gel never needs to be removed from the container in which it was originally formulated [4].

In bottle testing, gel strength is assigned a letter code of A through J. These codes ranges from highly flowing gel to rigid rubbery gel. Sydansk [4] reported that although two investigators may rate the same gel with different codes such as B and C at a time, it never happened that the same gel is rated by a

difference of two letters such as B and D by two investigators. The definition of these codes are stated below [4].

Code A **No detectable gel formed**: the gel appears to have the same viscosity (fluidity) as the original polymer solution and no gel is visually detected. .

Code B **Highly flowing gel** : the gel appears to be slightly more viscous (less fluid) than the initial polymer solution.

Code C **Flowing gel** : most of the obviously detectable gel flows to the bottle cap upon inversion.

Code D **Moderately flowing gel** : only a small portion (about 5 to 15 %)of the gel does not readily flow to the bottle cap upon inversion Usually characterized as a " tonguing " gel (i.e. after hanging out of jar, gel can be made to flow back into bottle by slowly turning bottle upright).

Code E **Barely flowing gel** : the gel can barely flow to the bottle cap and / or a significant portion (< 15 %) of the gel does not flow upon inversion.

Code F **Highly deformable nonflowing gel** : the gel does not flow to the bottle cap upon inversion.

Code G **Moderately deformable nonflowing gel** : the gel flows about half way down the bottle upon inversion.

Code H **Slightly deformable nonflowing gel** : the gel surface only slightly deform upon inversion.

Code I **Rigid gel** : There is no gel surface deformation upon inversion.

Code J **Ringing rigid gel** : a tuning-fork-like mechanical vibration can be felt after tapping the bottle.

4.2.2- PRE-GEL VISCOSITY MEASURMENT

Gel viscosity is measured using Wells-Brookfield cone / plate viscometer (spindle of cone / plate geometry type) which is shown in figure 4.1. Cone / plate geometry offers absolute viscosity determinations under conditions of defined shear rate and shear stress information that are readily avilable or can be calculated. The model used is HBT with 3.0 o cone spindle. This cone / plate model is cone # CP - 41 which requires 2 ml sample. Cone / plate geometry is suitable for advanced rheological analysis. The viscosity ranges that can be calculated using this model is from 0.983 cp to 196600 cp The viscosity will be measured at 40 ° C , 60 ° C and 90 ° C , and at different time.

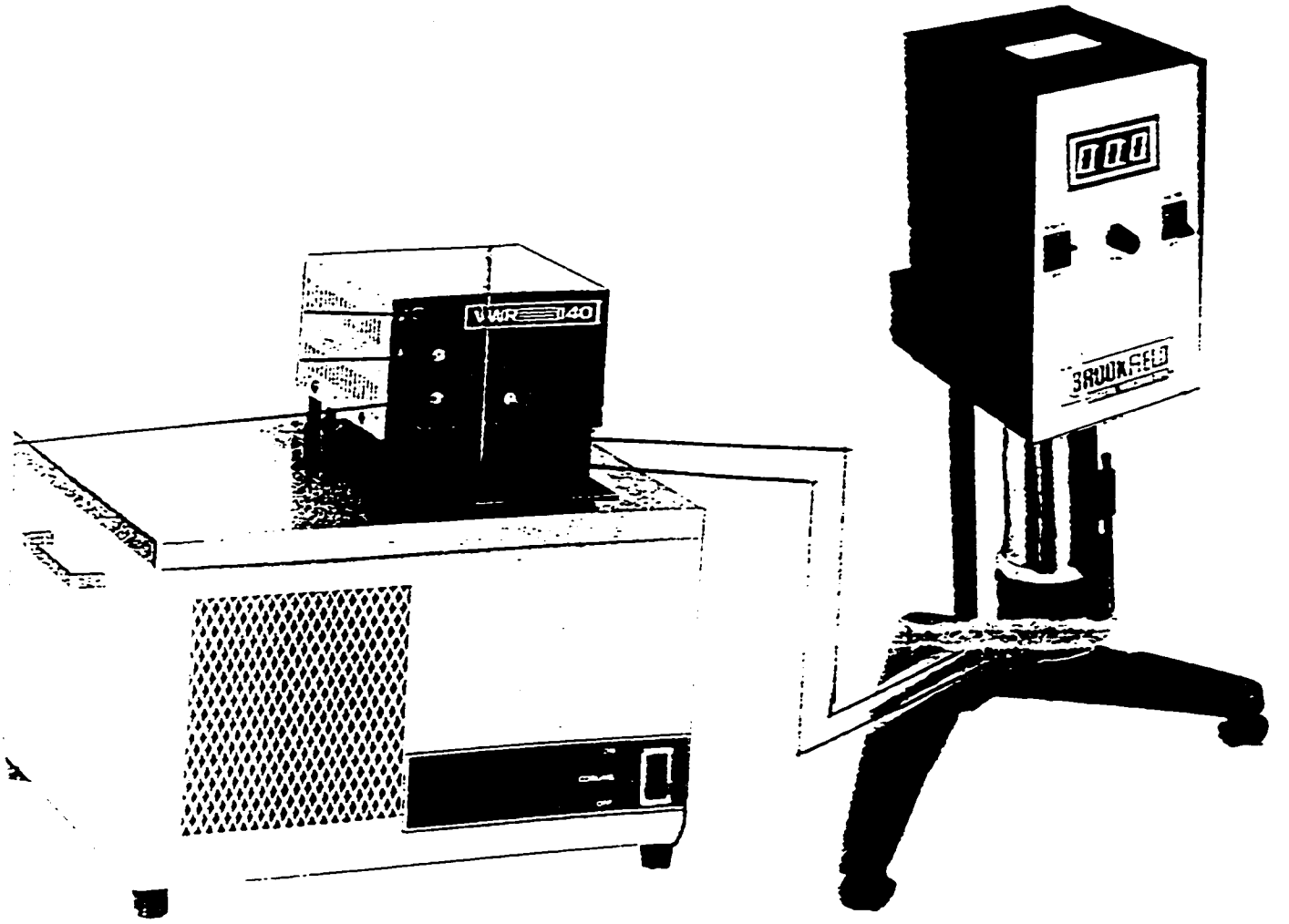


Figure 4.1 : Wells - Brookfield viscometer

4.3- COREFLOOD PROCEDURE

The experimental setup which was used to perform the coreflooding tests is shown in figure 4.2. The objective of the coreflood is to measuer the permeability reduction on a core samples of sandstone and limestone. Hassle core holder was used to confine the flooded core samples. The coreflooding setup consists of Hassle core holder, two transfer cells, an oven pressure gauge to measure the overburden and upstream pressure, transducer and a pump.The following core flood procedure was used to measure the permeability reduction at 90 ° C. .

1- The sample was saturated with brine

2- Absolute permeability for the brine was measured

3- Pregel solution of appropriate viscosity was injected through the core sample using appropriate flow rate.

4- The core was left for a period of time to allow gel formation

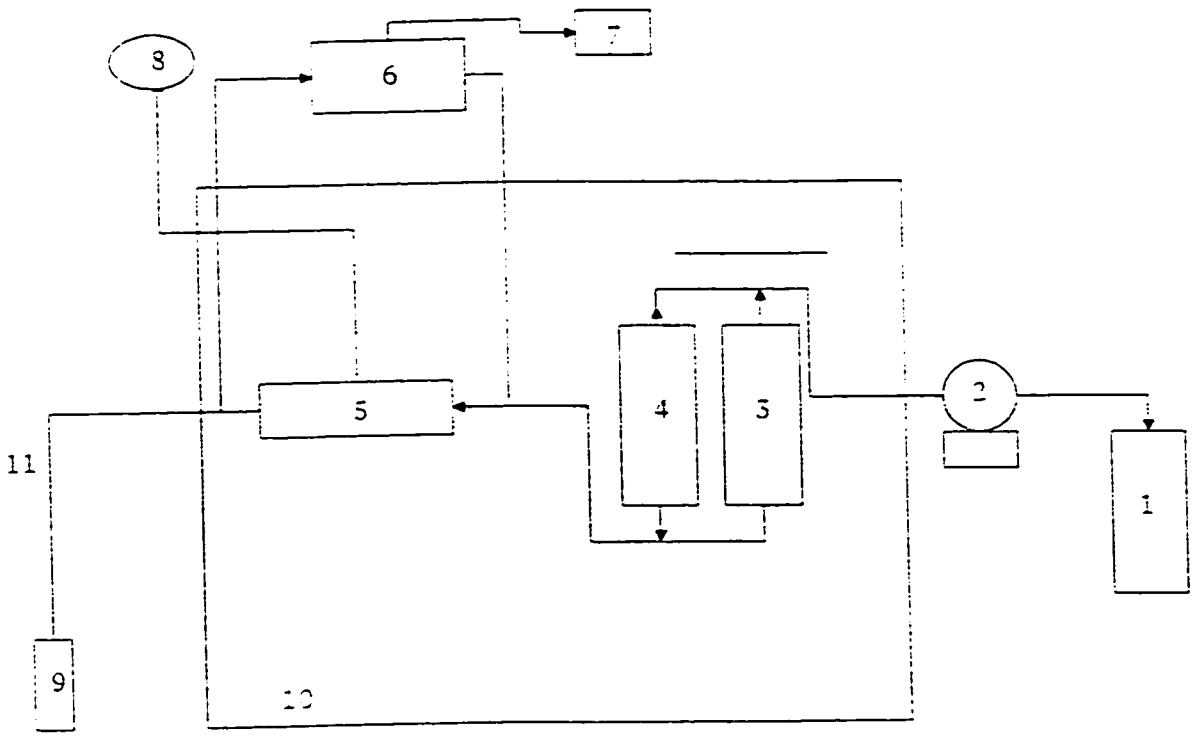
5- Finally the same brine was injected and the permeabilty was determined

6- Permeability reduction or gel plugging efficiency was calculated as folows

$$\text{permeability reduction} = (K_f / K_i)$$

where K_f = final permeability after gelation, md

K_i = initial absolute permeability, md



1- Beaker
2- Pump
3- Gel Transfer Cell
4- Brine Transfer Cell
5- Core Holder
6- Transducer
7- Pressure Difference Recordere
8- Pressure Gauge for Overburden
9- Tube Collector
10- Oven
11- Tube

Figure 4.2 : Coreflooding Setup

CHAPTER 5

CHAPTER 5

RESULTS AND DISCUSSION

This chapter is devoted to the discussions of the results of the measurements of gelation time, stability of polyacrylamide chromium (III) gel,. and the coreflood expriments. Several factors that affect gelation time and stability will be discussed. However, before discussing the results obtained, a brief discussion of the definition of gelation point and the sellection of sodium lactate as a retarder will be presented.

5.1- GELATION POINT

Gelation time is the most important parameter that should be considered while working with a gel system. Several methods and techniques had been used to define the gelation point. The gelation point is the point at which an abrupt increase in the viscosity of the gel occurs due to the chemical reaction of the chemical compounds (polymer, crosslinker and retarder) that will form the gel with time. Definition of the gelation time depends on either the viscosity of the gel

point or on the maximum infinite viscosity at which the gel will be unmobile (code I in bottle or Beaker testing procedure).

Each of these two definitions require continuous monitoring of gel formation or increase of viscosity with time. Determination of the gel point is quite subjective because it usually occurs over a period of time. Moreover, The time of gel point depends on the methods or techniques that are used to measure the gelling viscosity.

Measuring the viscosity with time by conventional viscometer is subjected to some limitations. The gelling viscosity is built up through a three-dimensional network reaction between the chemical compounds that will form the gel. The shear imposed during the viscosity measurements by using conventional viscometers will destroy the three-dimensional network being formed. This will increase the time required to define the gel point.

This drawback is avoided by evaluating the gelation time using bottle testing. This chapter contain many tables that present the evaluation of gelation time using bottle testing. Gels had been evaluated considering several parameters of the gelling process. These parameters are polyacrylamide concentration, chromium acetate concentration, sodium lactate concentration (retarder) and temperature. A wide range of process parameters concentrations and temperature have been investigated.

Moreover, this chapter presents the results of measuring gel viscosity at different shear rates, and temperatures. The range of shear rates investigated are from 1 to 200 S^{-1}. The experiments were carried out at 40 ° C, 60 ° C and 90 ° C

5.2- CHEMICALS SELECTION

5.2.1- Ligand Exchange

The polyacrylamide chromium (III) crosslinking is a discrete molecular chromium (III)-polymer complexes, therefore the crosslinking will display chemical reactivity characteristic of coordination complexes. Ligand exchange is an example of such reaction. Ligand exchange refers to the substitution of ligands bonded to a metal ion by other ligands in polymer solution. Ligand exchange chemistry process is represented in a general way in the following equation.

$$Cr(L)_n + m\,P\text{-}CO_2 \Leftrightarrow Cr(P\text{-}CO_2)_m + nL \qquad (1)$$

The ligand, L, is H_2O and OH if aqueous solutions of simple inorganic salts of chromium (III) ion are used and P-CO_2 is the polyacrylamide. The rate of gelation could be reuced by increasing the kinetic stability of the Cn(L)n by

judicious choice of the ligand L. An effective gelation delaying requires greater kinetic stability of the Cn (L)n but greater thermodynamic stability of the cross-linked polymer in order to displace the equilibrium in the above equation toward the right. The Cr (L)n having both greater kinetic as well as thermodynamic stability would not lead to gel formation. At moderate pH (4 - 7), the rate of gelation reaction is more controllable if chromium acetate is used in place of the hydrated chromium ion. This is attributed to the greater kinetic stability of chromium acetate in comperison to hydrated chromium ion. [10, 12]

5.2.2- Chromium Acetate

The introduction of chromium acetate complex is a major step toward the controlling of gelation reaction. The gelation time recorded using chromium acetate is longer compared to that obtained by using the hydrated chromium (III) ion. The gelation time is reduced approximately by a factor of 10 or more at low pH. Acetate is a relatively weak ligand toward chromium (III). This implies that the acetate will disociate from the chromium (III) ion during the gelling reaction leading to a shorter or faster gelation time. Acetate carboxylate is also in effective de-gelation agent. These property of acetate carboxylate will increase the stability of the gel. The complex chromium acetate resist precipitation at higher pH than

does the hydrated chromium (III) ion. Chromium acetate is relatively in expensive an readily available as a concentrated aqueous solution.[10,12]

5.2.3- Sodium Lactate

The enfluence of chromiumn lactate compared to chromiu acetate at 120 ° C was invistigate by Albonico et. al[14]. They reported only the relative time of lactate compared to acetate at one concentration. However, increasing the ratio of lactate to chromium will increase the gelation time appropriatle to place the pregel solution in the zone of interest.

The effect of sodium lactate on the chemical reaction in the following equation

$$Cr(L)_n + m\,P\text{-}CO_2 \Leftrightarrow Cr(P\text{-}CO_2)_m + nL$$

is to increase the thermodynamic stability of chromium acetate. The crosslinking process of chromium acetate and polyacrylamide will be delayed leading to an increase in the gelation time. Sodium lactate might shift the equilibrium of the chemical reaction in the above equation to the left hendering the formation of gel.

Chromium lactate is kinetically and thermodynamically more stable complex than the chromium acetate. Hence addition of lactate would result in

ligand exchange with acetate to form chromium (lactate)[3]. However, chromium lactate still remains thermodynamically less stable than Pa / Cr3+ complex but it will delay the gelation time more compared to chromium acetate for the reason mentioned above. Moreover, sodium lactate is commericially avilable and inexpensive.

5.3- RESULTS AND DISCUSSION

Each type of water shut off treatment requires a minimum time for pumping the pre gel solution and placing it in the desired location. The pumpability of this slug must be maintained during this process by ensuring that the gelation time starts only after the termination of the pumping operation. The pumping time depends on the volume of the treatment, the viscosity of the solution and other uncontrolable factors such as the fracture pressure of the treated formation.

In this study sixty experiments were conducted, fourty three were conducted to measure gelation time, nine experiments were conducted to measure the gel solution viscosity and eight expriments were carried out to determine the permeability reduction in sandstone and limestone cores. The gelation time was determined for different solutions of different polyacrylammide, chromium acetate and retarder concentrations. At the beginning a set of expriments at various ratios of polyacylamide to chromium acetate were carried out. These ratios were

investigated at room temperature(≈ 25 ° C) and at 60 ° C. The purpose of this step is to choose the ratio that will give the appropriate gelation time at the temperature of interest.

The ratio of polyacrylamide to chromium acetate was varied in such a way that a minimum and suitable time for the treatments is obtained. For deeper matrix treatments, the gelation time is controlled by adding an appropriate concentration of the retarder to increase. In this way, the gelation time can be increased such that the pre gel solution will not set before it reaches the target zones rerquired to be treated.

The required injection period for common treatments operations ranges from few hours to few days, depending on the radius of invasion selected and the thickness of zone to be treated, both of which determine the volume of treatment. Figure 5.1 shows the gelation time change with various ratios of polyacrylamide to chromium acetate at 25 ° C and 60 ° C. For the 60 ° C data, the ratios range (15 - 64) gives gelation times (5 - 10 hours). At low ratios the gelation times change sharply indicating high sensitivity to any small variation of the polyacrylamide or chromium acetate concentrations. A ratio of 30 (6.0 % polyacrylamide and 0.2 % chromium acetate) appeared to be appropriate. The rest of the experiments at 90 ° C and 120 ° C were carried out at this ratio with 1.0 %, 2.0 % and 3.0 % retarder concentrations.

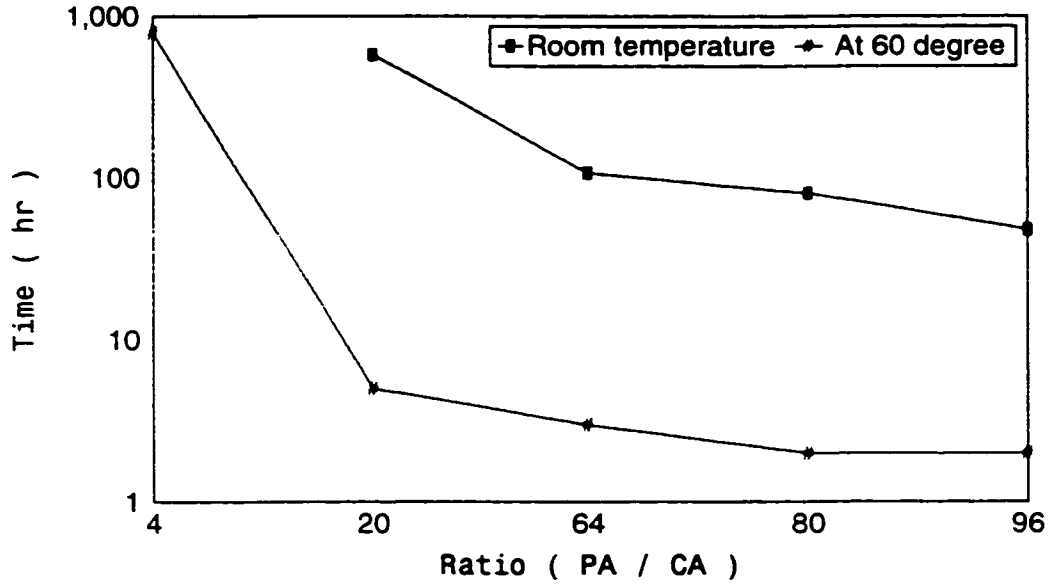


Figure 5.1 : Effect of the ratio of (PA / Cr) on gelation time

5.3.1- BOTTLE TESTING

5.3.1.1- Gelation Time

Bottle testing is a quick method used to screen gel solution over a wide range of temperatures and concentrations. It is also a cost effective method to study long term stability and gelation time. In this study a total of forty experiments were carried out using bottle testing procedure developed by Sydansk [4,8] . Twenty eight experiments were conducted at room temperature and 60 ° C for varios polyme and chromium concentrations. The expreriments at 60 ° C were carried out at sodium lactate concentrations varying between 1.0 wt. % to 10.0 wt. % but the gelation time was too large for some experiments, or the gel would not form. The purpose of these experiments was to chose the suitable ratio for further study. Based on the results of these experiments 6.0 wt.% polymer, 0.2 wt.% chromium acetate and 1.0 wt. %, 2.0 wt. % and 3.0 wt. % sodium lactate concentrations were chosen.

Comparing the data in tables 5.1 and 25. for the same composition (PA = 5 % , CA = 0.25 %) at two different temperatures (25 ° C and 60 ° C) shows that 24 days (gelatio time) were required for the solution at 25 ° C to reach gel strength code of I (unmobile gel). However , at 60 ° C the time required for the

solution to reach the same strength code is only 6 hours. It has been found that a rigid gel (strength code J) is formed for the same solution at 60 ° C. However, a rigid gel would not formed for the same solution at room temperature.

Data in table 5.3 shows the changes in the gel strength code for another solution (PA = 2.0 %, CA = 0.5 %) at 60 ° C. For this solution the time required to reach an I strength code (gelation time) was 33.0 days. It was found that this solution formed also a rigid gel(code J).

5.3.1.2- Stability

Visual inspection for the stability of the three solutions shown on table 5.1, 5.2 and 5.3 was investigated. The stability for the three solutions was found to be 120 days, 65 days and 72 days respectively. The air was not removed from the vails and tha vails the vails were not sealed completely. Solution of table 5.2 was less stability (65 days) than the solution of table 5.1 which has the same concentrations. The reduction of stability reflect the effect of temperature on the stability in the presence of the air at the top of the solution. At high temperature the degelation process is faster than that at low temperature. As a result of this the stability at high temperature is less than the stability at low temperature for the same solution composition. The stability is illustrated by maintaining the same

volume and character. If the volume starts to shrink or some bubbles of liquid start to appear this is an indication of the time at which the gel starts to loose its stability. More detials about bottle testing measurments is found in appendix B.

Bottle testing procedure is used to determine the gelation time at different temperature. Long term stability up to 4.0 months at 60 ° and up to 2.0 months at 90 ° C has been demonstrated for the formulated gel in this study as shown in table 5.4. At 120 ° C it was not possible to evaluate the stability because the solution in the vial evaporated qiuckly. The key to high temperature stability is the removal of oxygen prior to sealing the vails. Oxygen removal can be done by careful vacuum degassing. This gel remained stable for 1.5 years to the date of observation. at room temperature (25 ° C)..

Several factors affect the stability of gels., These factors are The presence of air in the samples and polymer hydrolysis which is rapid at 90 ° C and above. The presence of air in gel solution leads to degradation of gel molecules and degelation of the formed gel at elevated temperature.

Therefore, these factors should be avoided or the effect of them should be minimized. The presence of air could be removed or reduced from gel solution. The polymer that has much more resistance to hydrolysis should be chosen. Also the retarder or the delaying agent that enhance the stability of the gel solution should be used.

Table 5.1: Gelation time measurements

Temperature = room temperature (25 ° C)
Polymer concentration = 5.00 %
Chromium concentration = 0.25 %

TIME	CODE
1 hour	A
2.5	A
4	A
6	A
8	A
10	A
12	A
14	A
24	A
24	A
3 days	A
4	A
6	A
10	A
14	C
15	F
16	G
18	G
20	H
21	H
22	H
24	I

Table 5.2 : Gelation time measurements

Temperature = 60 ° C
Polymer concentration = 5.0 %
Chromium concentration = 0.25 %

TIME	CODE
1 hour	**A**
1.5	**A**
2.5	**B**
3	**C**
4	**G**
5	**I**
6	**J**

Table 5.3 : Gelation time measurments

Temperature = 60 ° C
Polymer concentration = 2.0 %
Chromium concentration = 0.5 %

TIME	CODE
1 hour	A
1.5	A
2.5	A
3	A
4	A
5	A
14	A
25	A
2 days	A
3	A
5	A
8	A
11	B
12	C
13	E
15	F
17	G
23	H
33	I
34	J

Table 5.4 : Gel Stability

System	Cr acetate %	PA %	Na Lactate %	Temp.° C	Stability Days
1	0.2	6.0	2.0	90	60
2	0.2	6.0	1.0	90	60
3	0.2	6.0	0.0	90	40
4	0.2	6.0	2.0	60	120
5	0.2	6.0	1.0	60	120
6	0.2	6.0	0.0	60	90
7	0.125	5.0	0.0	60	90
8	0.5	5.0	0.0	60	72
9	0.25	5.0	0.0	60	65
10	0.5	2.0	0.0	60	38
11	0.5	5.0	0.0	25	1.5 year

5.4- FACTORS AFFECTING GELATION TIME

5.4.1- EFFECT OF THE CONCENTRATION

The effect of different concentrations of polyacrylamide and chromium acetate on gelation time wwas investigated. The gelation time increased with decreasing polyacrylamide concentrations. Figure 5.2 shows that the gelation time increases as polyacrylamide concentration decreases. However, The gelation time increases as chromium acetate concentration increases. This behavior is shown on figure 5.3.

According to kinetic theory, increasing initial reactant concentration, the time required to shift the reaction in the folloing equation

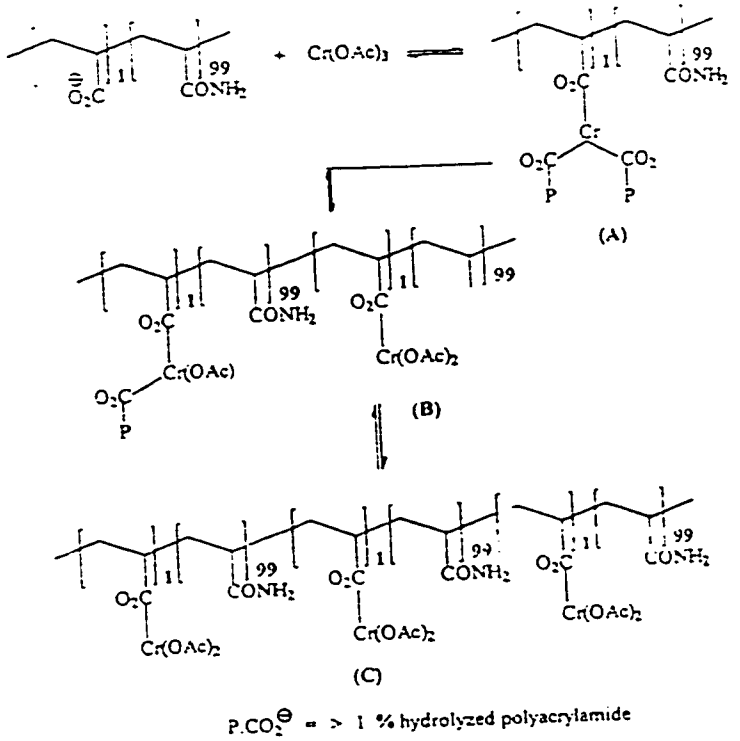
$$Cr(L)_n + m\,P\text{-}CO_2 \Leftrightarrow Cr(P\text{-}CO_2)_m + nL$$

to the right decreases. This is true for initial polymer concentration and Cr ion concentration.[1] However the inference of kenitic theory is not applicable to chromium acetate concentration.

Increasing concentration of chromium acetate is supposed to shorten the gelation time. In literature. Terry et. al.[1] found that as the concentration of chromium ion increased, the gelation time increased. Quite interestingly the

gelation time becomes longer in our experiments (see figure 5.3). A pluasible explianation is depicted in scheme below.

At limiting concentration of $Cr(OAc)_3$, the PCO^-_2 ligand will displace all the acetate to form the crosslinked species A. However as the concentration of $Cr(OAc)_3$ increases the avilable polyacrylamide does not have enough PCO^-_2 ligand to displace all the acetate ligand and as such with increasing $Cr(OAc)_3$ concentration more and more lesser crosslinked species B and C will be generated. Species A. B and C are all in eqiulibrium and eventually the B and C will go back to A because of its greater thermodynamic stability. However. this process causes a delay in the gelation time because B and C are expected to be formed faster(kinetically more stable)..



The effect of the concentration on gelation time has the same trend regardless of the temperature. At 60 ° C the gelation time increases as the concentration of polyacrylamide decreases and increases as the concentration of chromium acetate increases as shown on figures 5.2 and 5.3. However, the gelation time at 60 ° C was shorter than the gelation time at room temperature(≈ 25 ° C).

5.4.2- EFFECT OF TEMPERATURE

The temperature was varied from room temperature to 120 ° C. The experiments were carried out at room temperature (25 ° C.) , 60 ° C, 90 ° C. and 120 ° C. Within this range of temperature it was found that as the temperature increases the gelation time decreases. The trend of the effect of the temperature on gelation time is the same wether the retarder is added to the solution or not. Figure 5.4 shows the effect of temperature on gelation time at various retarder concentrations.

According to Arrhenius equation given below, many homogeneous chemical reactions are affected by temperature as follows:

$$d (Ln\ k)/ d (1/T) = - Q /R \qquad (2)$$

Where Q is the energy of activation (cal / g mol)

k is specific rate [min^{-1} ($g/m^3)^{1-n}$]

T is the absolute temperature (k)

R is ideal gas constant 1.986 (cal / g mol k)

For n^{th} order of reaction the following expression was assumed for gelation time.

$$(dx/ dt) = k (a - x)^n \qquad (3)$$

Where

a = the initial concentration of the reacting species g/ m^3

x = the amount of the reacting species which has reacted at any particular time g / m^3 and

t = the reacting time, min

Integrating equation 3 and rearranging the variable, the following equation is obtained

$$Ln\ t' = Ln\ c' - Ln\ k - (n -) Ln\ a \qquad (4)$$

From equation 4 and equation 2 the following equation can be obtained

$$Ln\ t' = Q / RT - (n - 1) Ln\ a + c" \qquad (5)$$

Equation 5 can be differentiated with respect to 1/T , the following equation can be obtained fro gelation time

$$Q\ d(1 / T) = R\ d\ Ln\ t' \qquad (6)$$

According to equation 6 if the temperature increases the gelation time is decreases. [2]

5.2.1.3- EFFECT OF RETARDER

The effect of retarder as a delaying agent was investigated. Different concentrations of sodium lactate were mixed with the solution of polyacrylamide and chromium acetate. AT 60 ° C and 6.0 % wt. polyacrylamide and 0.2 % wt. chromium acetate, the gelation time increased from 1.5 hours without retarder to 85 hours for 1.0 wt. % sodium lactate. However for 2.0 Wt. % 3.0 Wt. % sodium lactate the time increased to 216 hours and to 360 hours respectively. The gelation time decreased with increasing temperature if the retarder concentration in the solution was kept constant. Figure 5.5 illustrates that the gelation time increases as sodium lactate concentration increases.

Expriments also have been conducted to study the effect of sodium lactate at high temperatures at the same concentrations of polyacrylamide and chromium acetate. At 90 ° C The effect of sodium lactate on gelation time was less comared to its effect at 60 ° C. For 1.0 wt. % sodium lactate, the gelation time was 45 hours. At 2.0 wt. % sodium lactate the gelation time increased to 96 hours. The gelation time was 156 hours for 3.0 wt. % sodium lactate. The gelation time at 90 ° C decreased by a factor of approximately 2.5 compared to that at 60 ° C for all sodium lactate concentrations.

Moreover, The effectiveness of sodium lactate as a delaying agent was also tested at 120 ° C. In thes expriments the gelation time decreases sharply

compared to the gelation time at 60 ° C and 90 ° C. The gelation time for 1.0 wt. % sodium lactate was only 2.0 hours compared to 45 hours at 90 ° C and 85 hours at 60 ° C. For 2.0 wt. % and 3.0 wt. % sodium lactate the gelation time was 6.0 hours and 9.0 hours respectively at 120 ° C.

The effect of sodium lactate on the chemical reaction in the following equation

$$Cr(L)_n + m\,P\text{-}CO_2 \Leftrightarrow Cr(P\text{-}CO_2)_m + nL \qquad (1)$$

is to increase the thermodynamic stability of chromium acetate. The crosslinking process of chromium acetate and polyacrylamide will be delayed leading to an increase in the gelation time. Sodium lactate might shift the equilibrium of the chemical reaction in equation 1 to the left hendering the formation of gel.

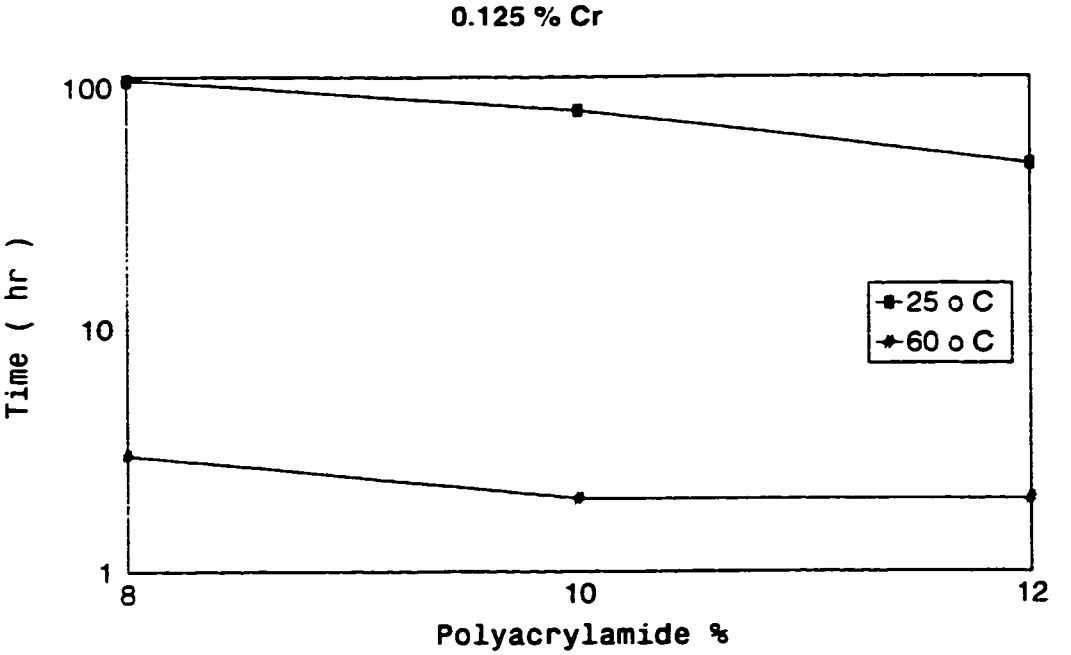


Figure 5.2 : Effect of Polyacrylamide concentration

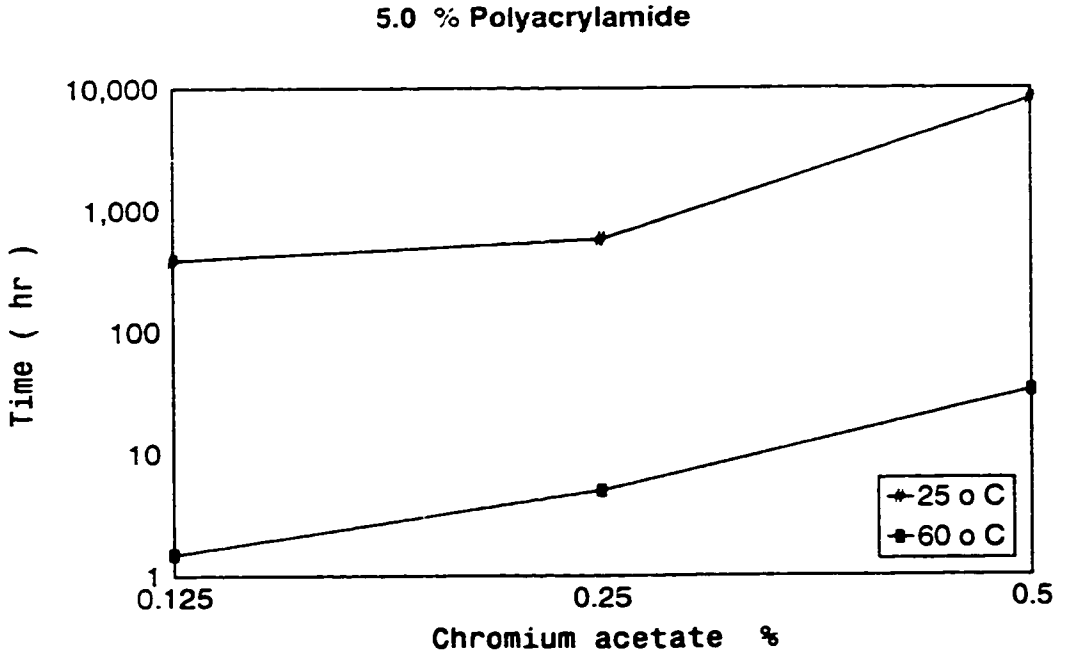


Figure 5.3 : Effect of chromium concentration

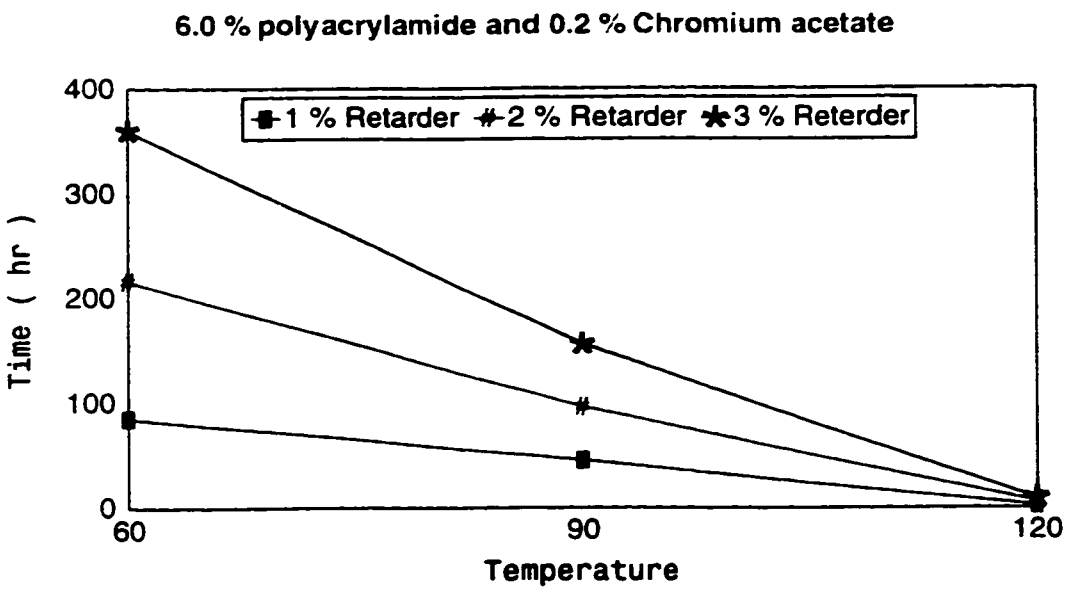


Figure 5.4 : Effect of Temperature on gelation time

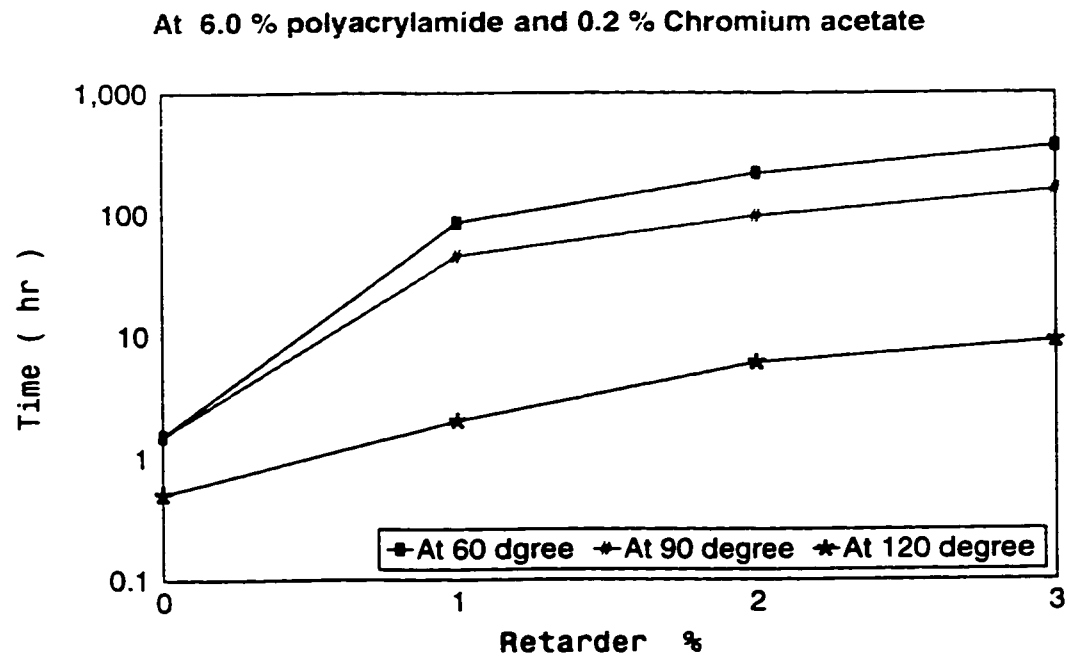


Figure 5.5 : Effect of retarder on gelation time

5.5-GEL VISCOSITY

Solution gel viscosities were measured using cone-and-plate type viscometer. Viscosities were measured at various shear rate for 6.0 % polyacrylamid and 0.2 % chromium acetate. The concentrations of sodium lactate that were used were 1.0 %, 2.0 %, and 3.0 %. The temperature was also varied for each gel formulation. The ranges of shear rate varied from 1.0 1/s to 200.0 1/s. The effect of shear rate on solution gel viscosities was destructive. As shear rate increases the viscosity of gel solution decreases at constant temperature.

A total of nine experiments were carried out. The viscosity in each experiment was measured at different times. At the beginning, the time difference between two successive measurement was small (0.5 hours and 1.5). At higher time the time difference between two successive measurements was 3.0 hours. The total number of viscosity data points measured were about 600.0 data points.

Figure 5.6 shows the viscosity of gel solution at 40 ° C versus shear rate as a function of time This figure indicates that at a constant shear rate the viscosity increases substantially from 0.5 hour to 33.0 hours. On this log - log plot the approximate straight line trend suggests that a power law model describing pseudoplastic fluid is applicable to the pre gel solution within the range studied. It is also noted that the difference of the viscosity at the different times is more at low shear than of that difference at high shear. This argument is supported by

viscosity data on figure 5.7. In this figure solution viscosities is plotted versus time at constant shear and temperature. Solution viscosities increase with time. The effect of shear rate on gelation rate and the viscosity of gel solution is clearly demonstrated. .

Figure 5.8 shows the effect of shear rate on viscosity at 60 ° C. The effect of shear rate on viscosity at a temperature of 60 ° C is more than at a temperature of 40 ° C. Comparing the gel solution viscosities plotted on figure 5.9 it noticed that the viscosity decreases sharply as the shear rate increases, It appears that the viscosity is very sensitive to the shear at both temperature. The data points were measured at 0.5 hours.

Figure 5.10 shows viscosity change with time at different shear at 60 ° C . Comparing the gel solution viscosities at different temperature and 1.0 wt. % retarder concentration as shown in figure 5.11, it was found that the increase in temperature increases the gel viscosity sharply. This argument is supported by comparing the gelation time in this figure. To reach 200,000 cp, 0.5 hour is required at 90 o C compared to 6.0 hours at 60 ° C. This means that the gelation time at 60 ° C approximately eleven times greater than the gelation time at 90 ° C. At 40 ° C, The gelation time required was even more. To reach approximetely 15, 000cp , the time reqiured was 33 hours.

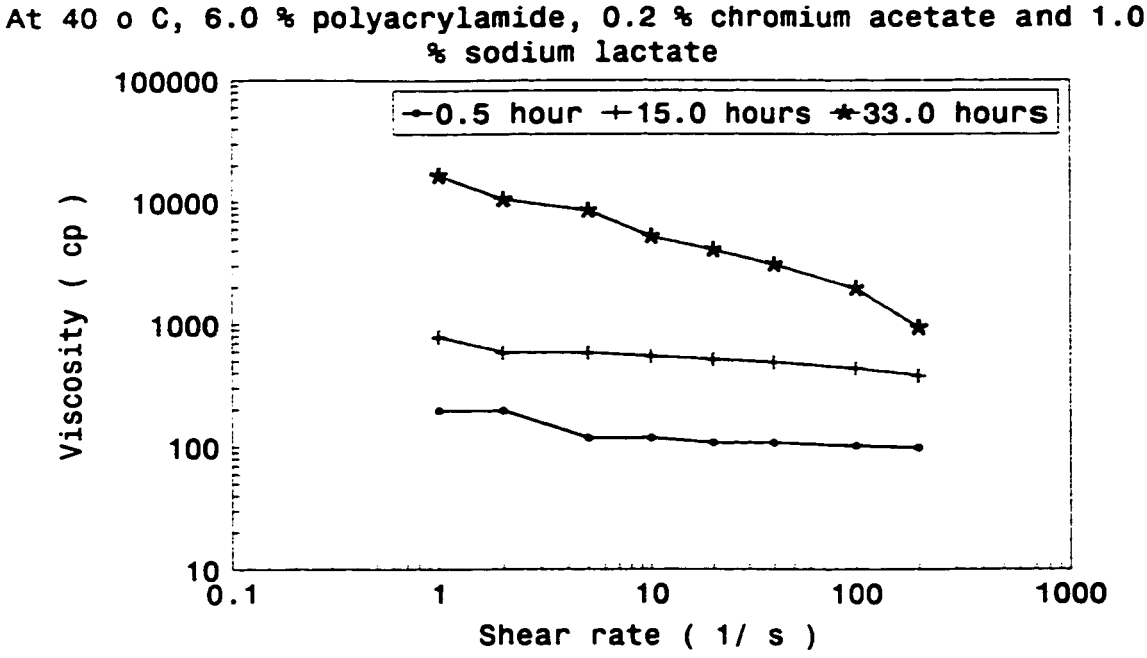


Figure 5.6 : Effect of shear rate on viscosity

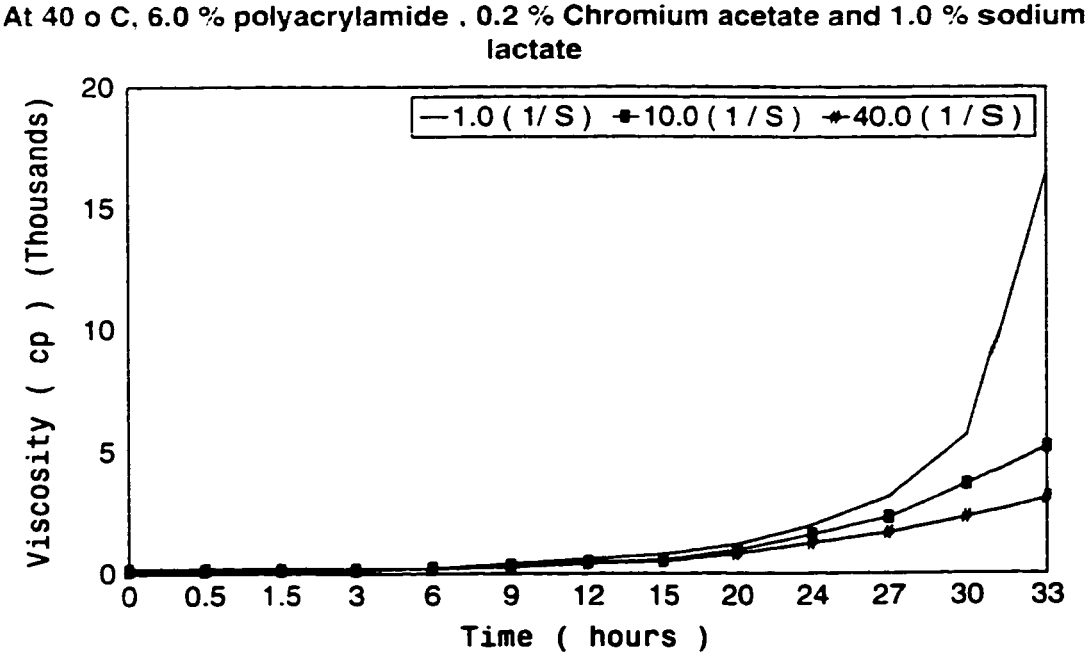


Figure 5.7 : Viscosity (cp) Vs. Time (hours)

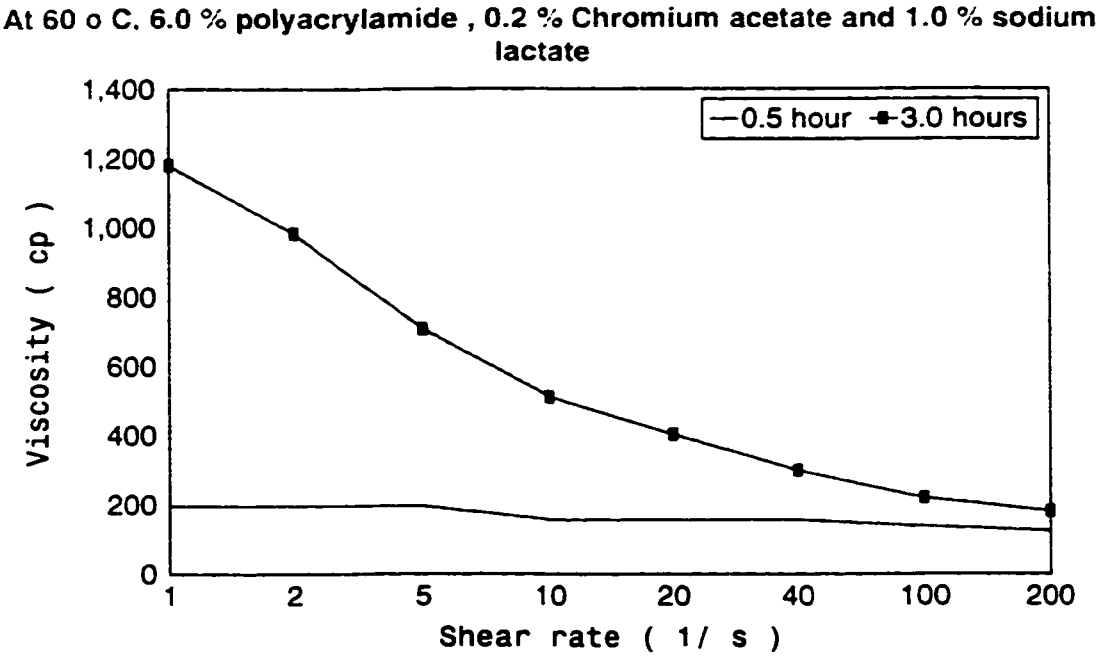


Figure 5.8 : Effect of shear rate on Viscosity

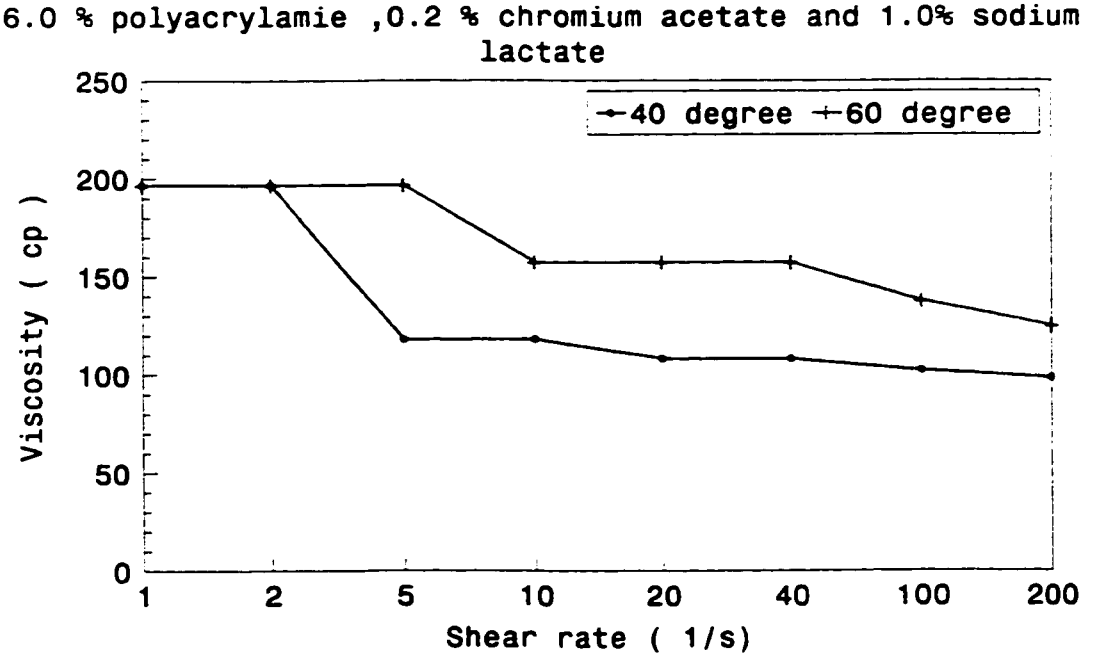


figure 5.9 : Effect of shear on viscosity

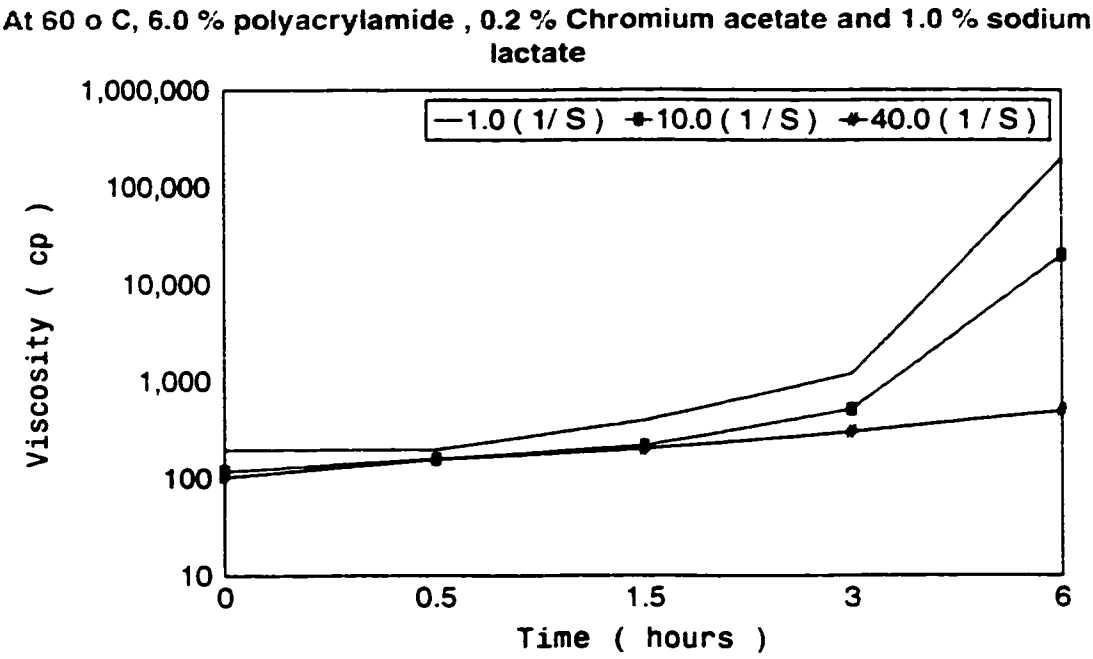


Figure 5.10 : Viscosity (cp) Vs. Time (hours)

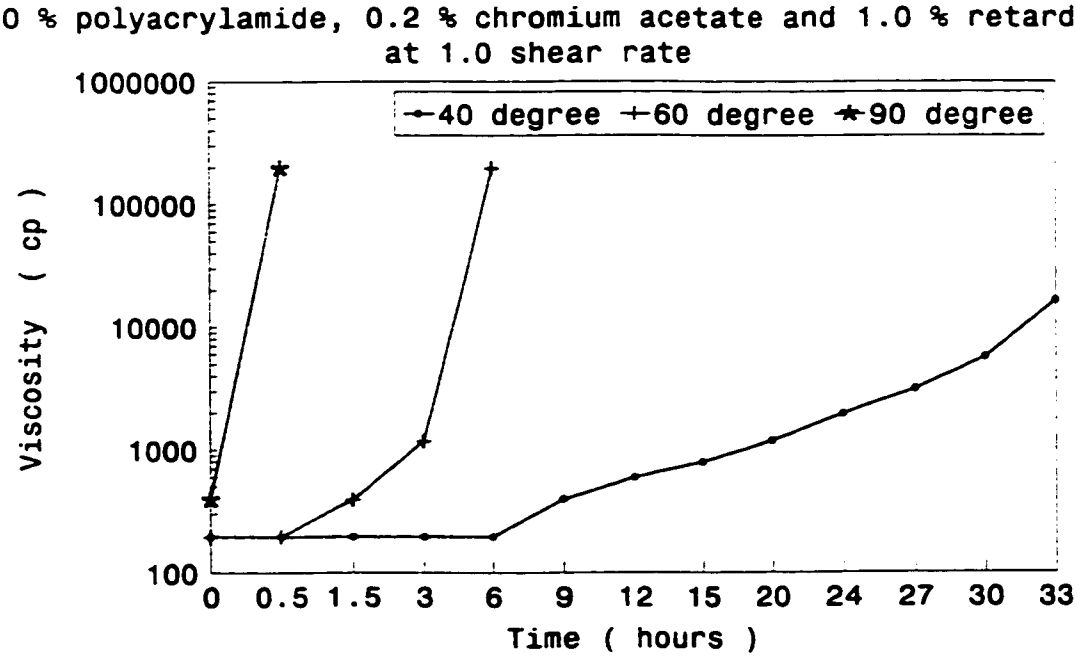


Figure 5.11 : Effect of temperature on gel viscosity

The concentration of the retarder (sodium lactate) is increased to 2.0 % and gel solution viscosity is measured at different shear rates and different temperatures. Figures 5.12 and 5.13 show the effect of shear rate on gel solution viscosity at 40 ° C and 60 ° C respectively. The effect of shear on gel solution viscosity of 2.0 % retarder has the same trend as gel solution with 1.0 % retarder. Figure 5.14. 5.15 and 5.16 show the change of gel solution viscosity with time at different shear at 40 ° C, 60 ° C and 90 ° C respectively.

Figures 5.17 and 5.18 show the effect of shear rate on gel viscosity of 3.0 % sodium lactate at 40 ° C and 60 ° C. Figures 5.19, 5.20 and 5.21 show the change of gel solution viscosity of 3.0 % sodium lactate with time at 40 ° C, 60 ° C and 90 ° C.

Testing the effect of temperature on solution gel viscosities, it was found that the solution gel viscosities increased with temperature. These results are shown on figures 22.

The viscosity of the solution decreases as the retarder concentration increases while the temperature , time of measurements and the shear rate were kept constant, as demonstrated in tables 5.5, 5.6 and 5.7. At 33.0 hours the gel viscosities are 16514.4 cp, 5111.6 cp and 1966.0 cp for 1.0 %, 2.0 % and 3.0 % retarder concentrations rescectively., The viscosity at 1.0 % retarder is approximately 3 time and 8 times more than the viscosity at 2.0 % and 3.0 %

retarder respectively. More details about gel viscosity measurements and the change of gel viscosity with time and with shear is found in appendix C.

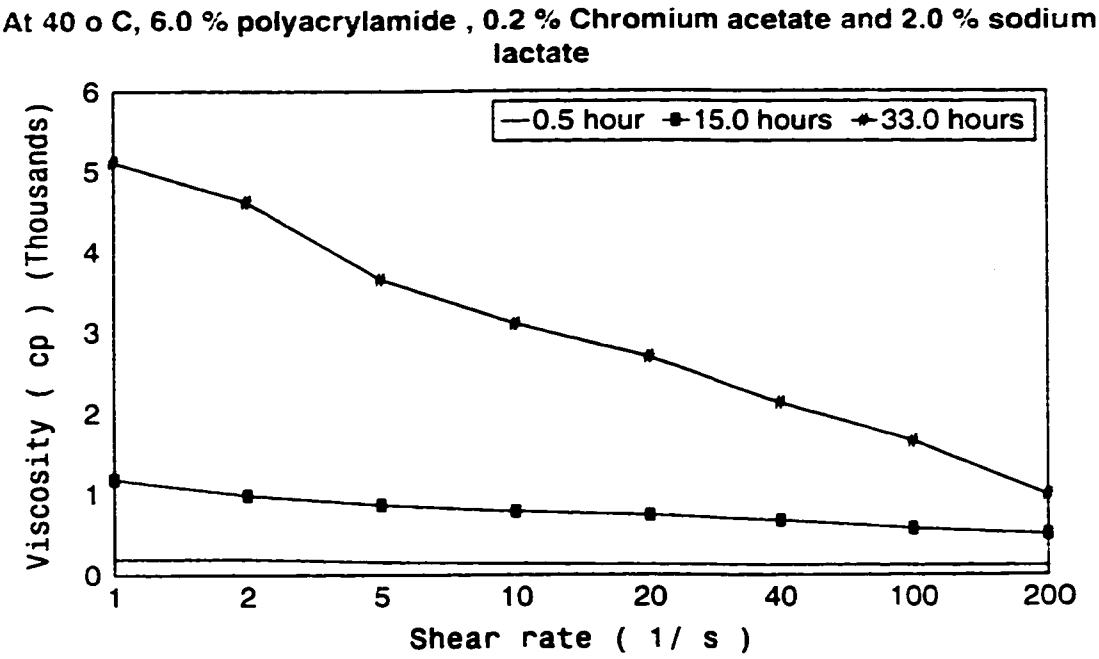


Figure 5.12 : Effect of shear rate on Viscosity

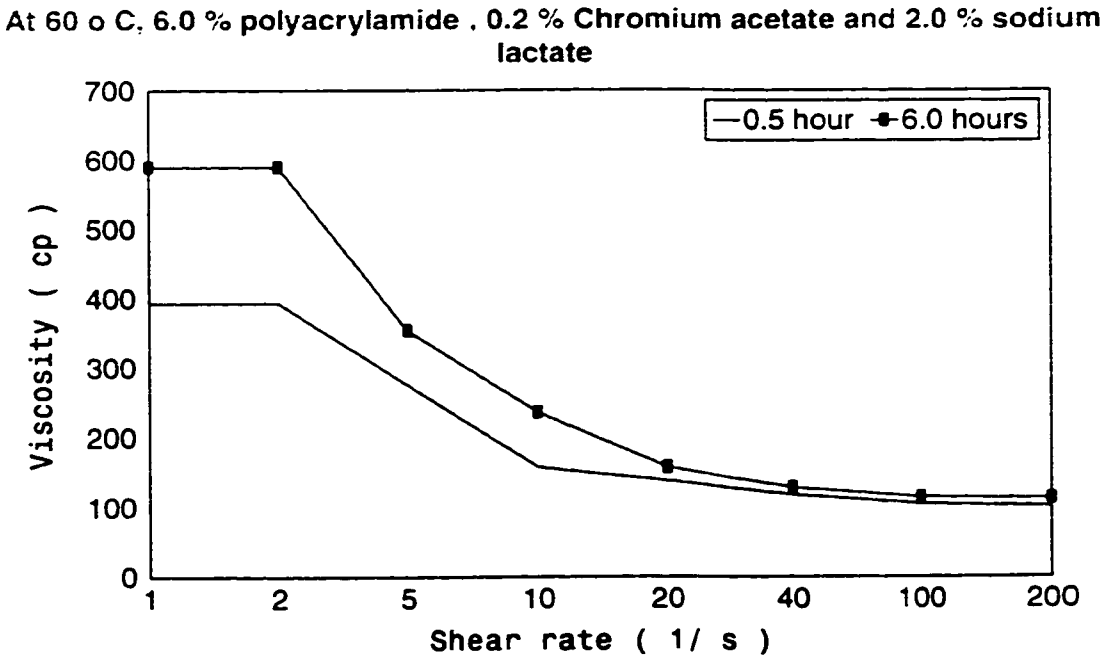


Figure 5.13 : Effect of shear on viscosity

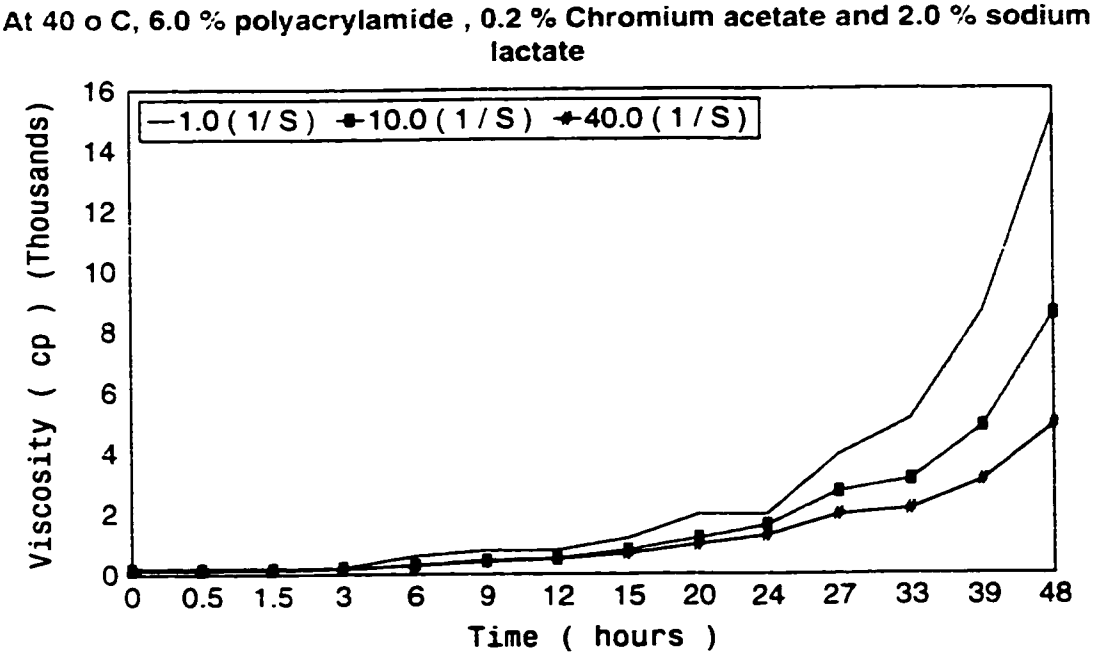


Figure 5.14 : Viscosity (cp) Vs. Time (hours)

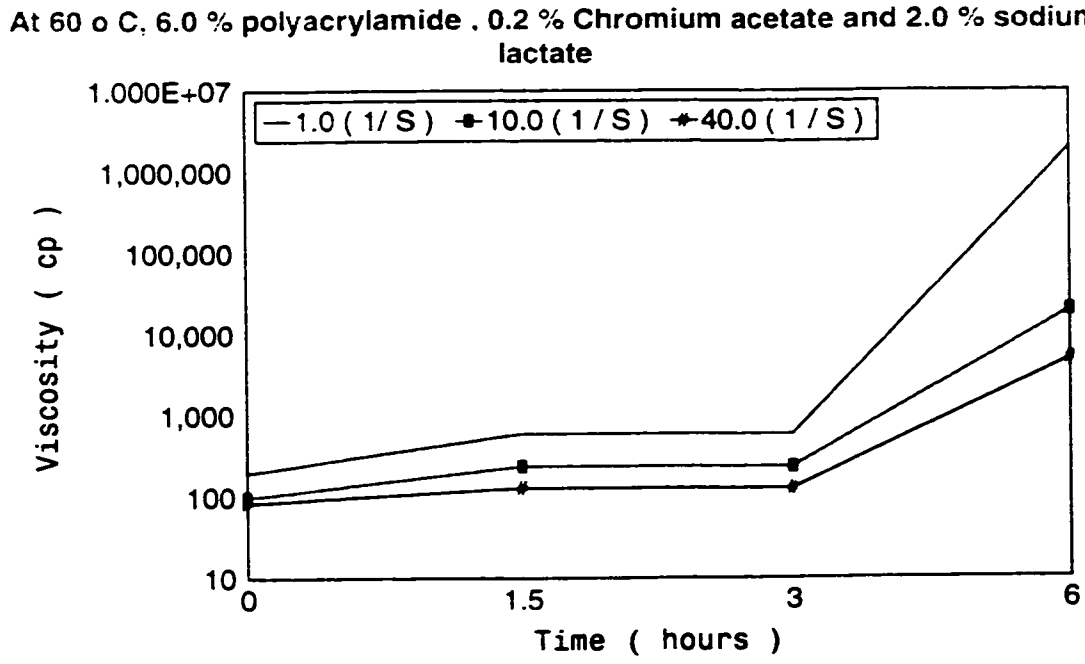


Figure 5.15 : Viscosity (cp) Vs. Time (hours)

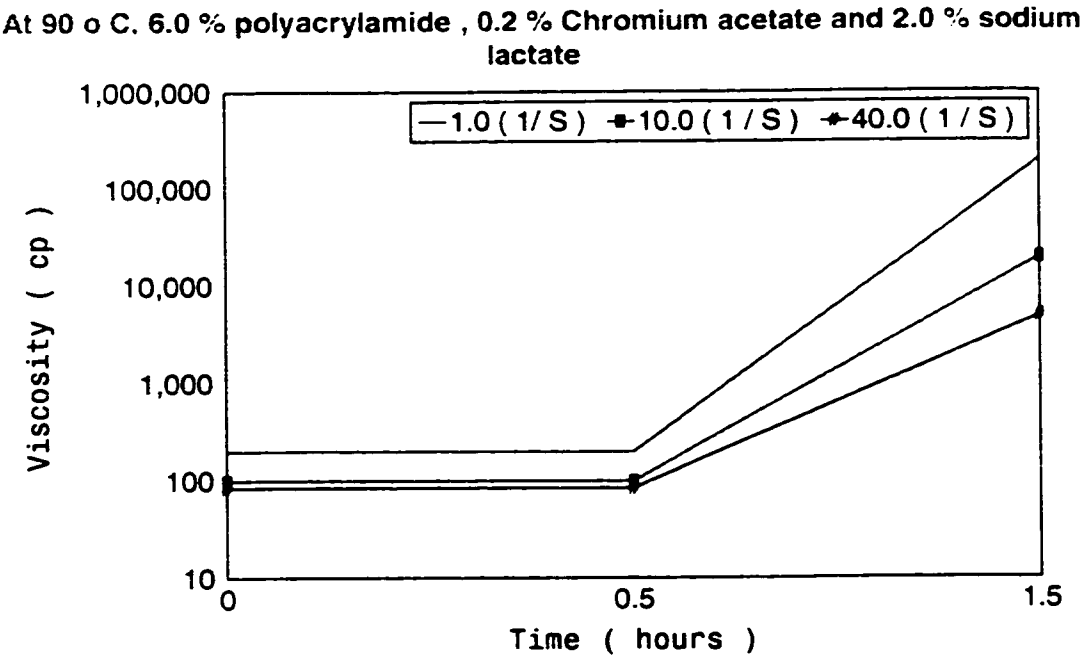


Figure 5.16 : Viscosity (cp) Vs. Time (hours)

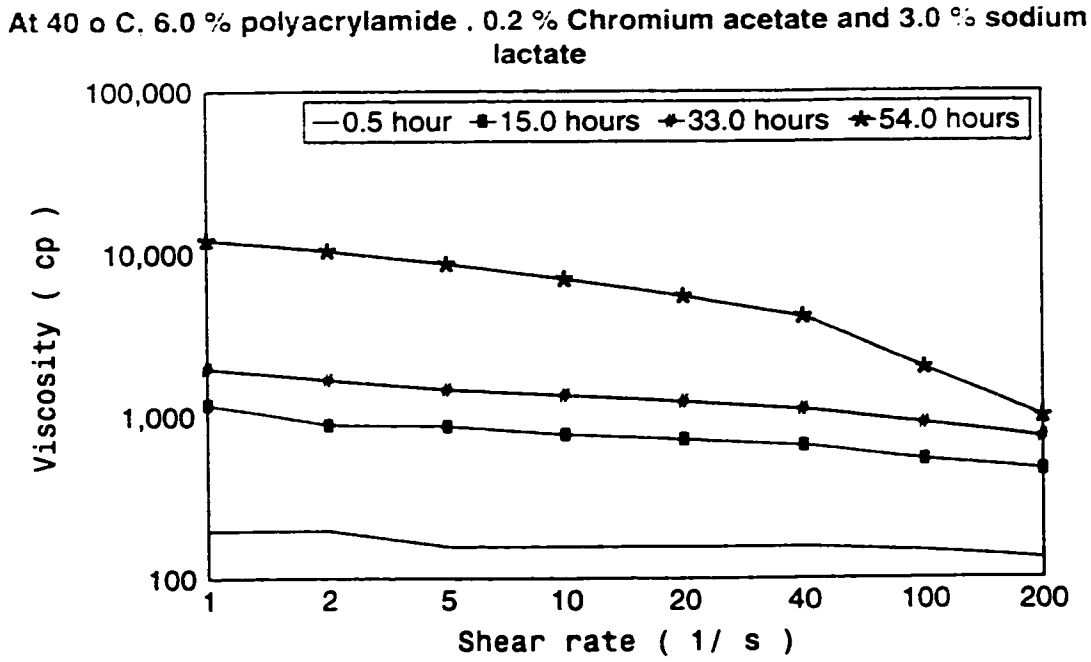


Figure 5.17 : Effect of shear rate on viscosity

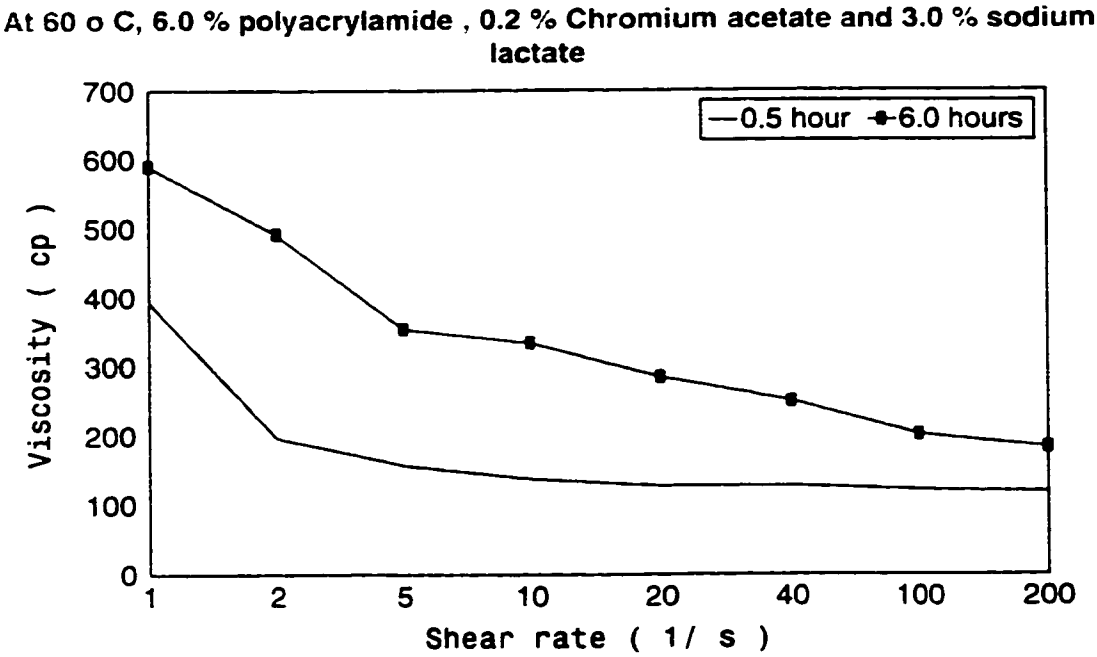


Figure 5.18 : Effect of shear rate on viscosity

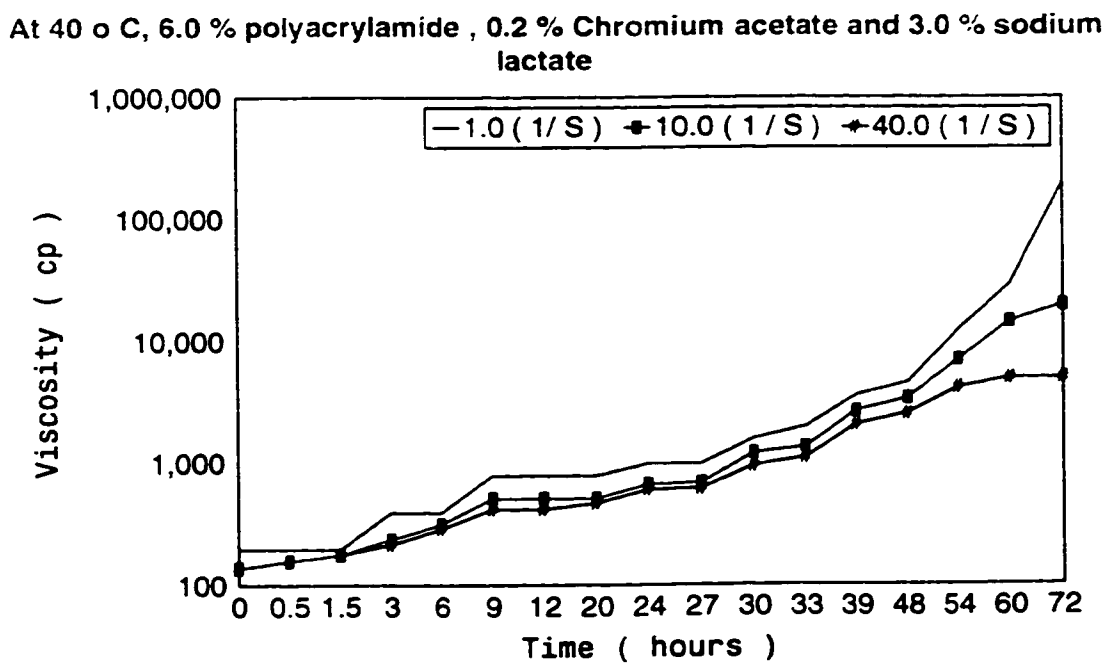


Figure 5.19 : Viscosity (cp) Vs. Time (hours)

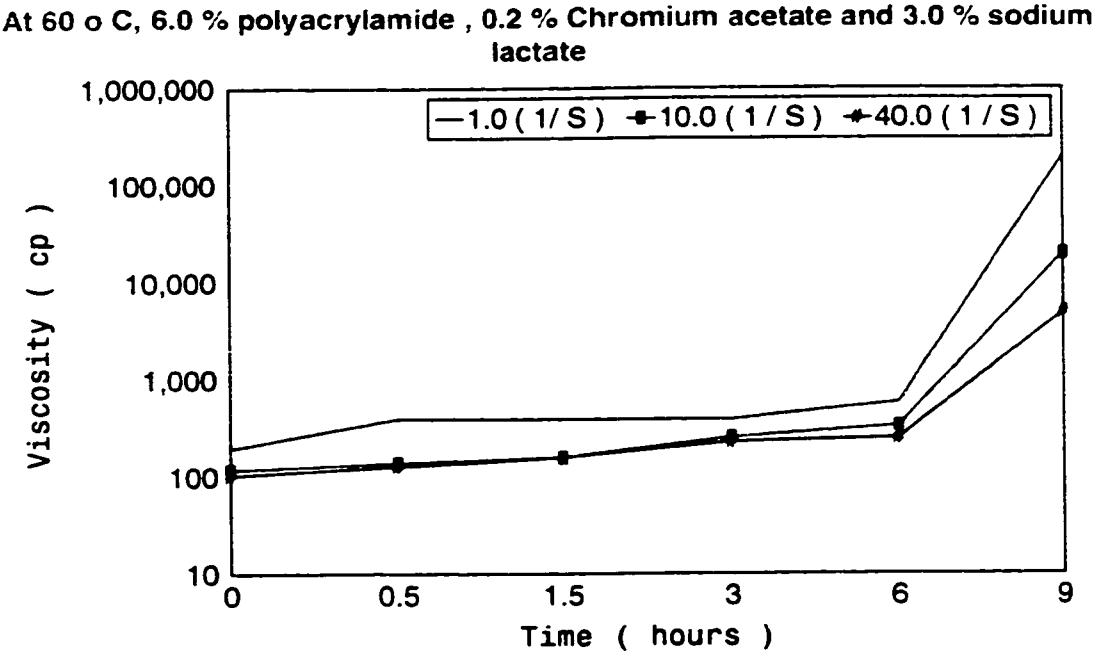


Figure 5.20 : Viscosity (cp) Vs. Time (hours)

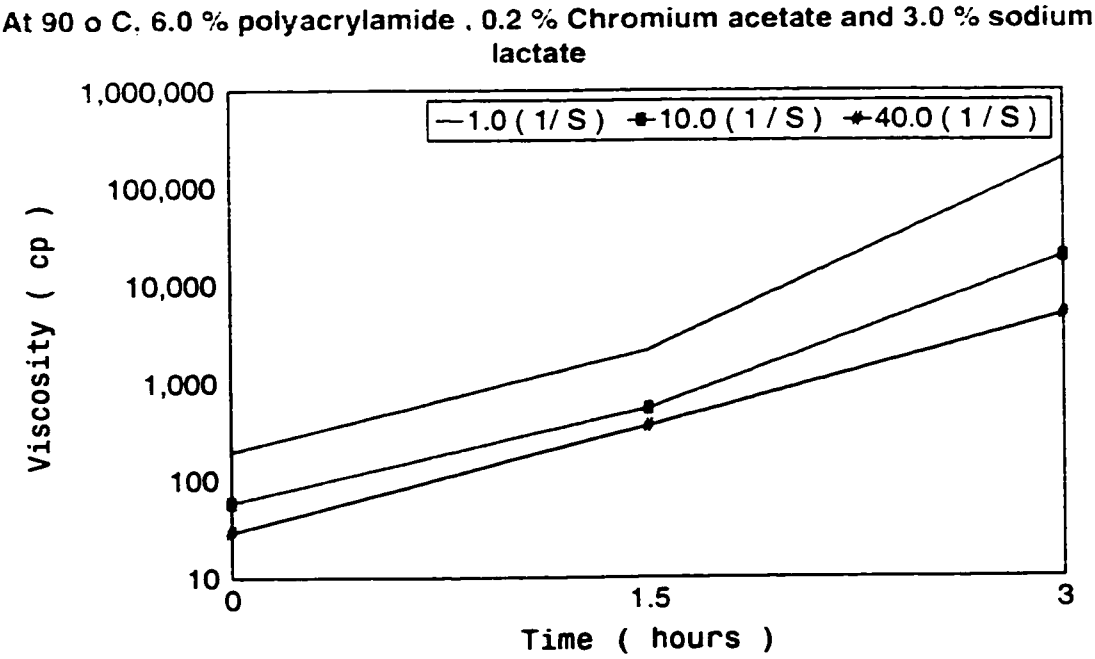


Figure 5.21 : Viscosity (cp) Vs. Time (hours)

At 6.0 % polyacrylamide , 0.2 % Chromium acetate , 40.0 shear and 0.5 hours

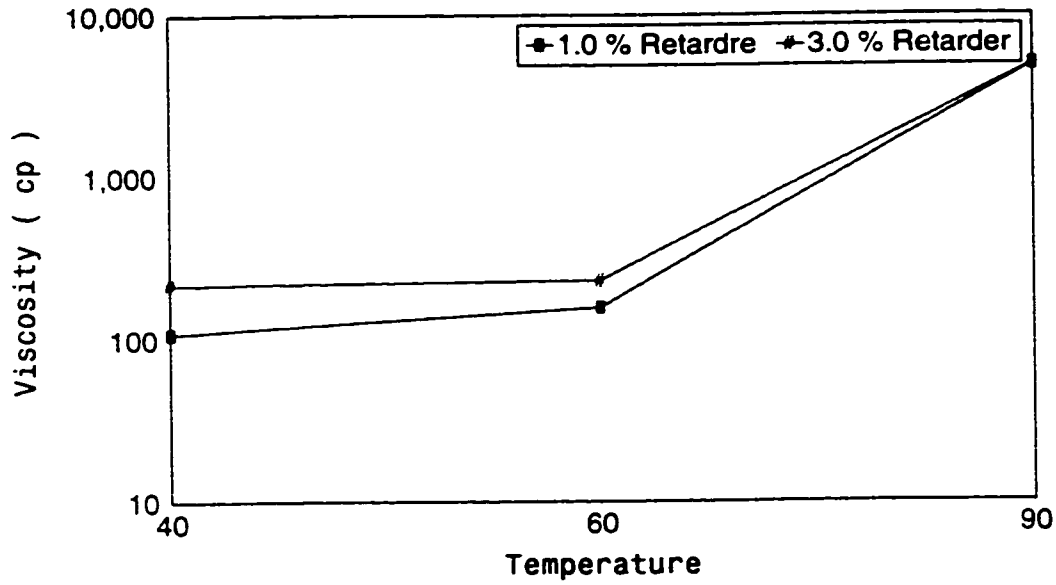


Figure 5.22 : Effect of temperature on gel viscosity

Table 5.5 : Gel viscosity measurments

Chromium concentration = 0.2 %
Polymer Concentration = 6.0 %
Lactate Concentration = 1.0 %
Temperature = 40 ° C

Time (hours)	Viscosity (cp) shear =1 (1/s)	Viscosity (cp) shear = 10 (1/s)	Viscosity (cp) shear = 40 (1/s)
0.0	196.6	117.96	108.13
0.5	196.6	117.96	108.13
1.5	196.6	117.96	113.05
3.0	196.6	137.62	127.79
6.0	196.6	196.6	191.69
9.0	393.2	314.56	275.24
12.0	589.8	471.84	417.78
15.0	786.4	550.84	491.5
20.0	1179.6	943.68	801.15
24.0	1966.6	1592.46	1243.5
27.0	3145.6	2300.22	1676.02
30.0	5701.4	3656.36	2295.68
33.0	16514.4	5209.9	3081.71

Table 5.6 : Gel viscosity measurements

Chromium concentration = 0.2 %
Polymer Concentration = 6.0 %
Lactate Concentration = 2.0 %
Temperature = 40 ° C

Time (hours)	Viscosity (cp) shear =1 (1/s)	Viscosity (cp) shear = 10 (1/s)	Viscosity (cp) shear = 40 (1/s)
0.0	196.6	137.62	122.88
0.5	196.6	137.62	122.88
1.5	196.6	157.28	137.62
3.0	196.6	196.6	176.94
6.0	589.8	294.9	275.24
9.0	786.4	452.18	417.78
12.0	786.4	511.16	501.33
15.0	1179.6	786.40	673.36
20.0	1966.0	1179.6	968.26
24.0	1966.6	1612.12	1268.07
27.0	3932.00	2713.08	1951.26
33.0	5111.6	3106.28	2128.20
39.0	8650.4	4875.68	3086.62
48.0	15138.2	8571.76	4915.0

Table 5.7 : Gel viscosity measurements

Chromium concentration = 0.2 %
Polymer Concentration = 6.0 %
Lactate Concentration = 3.0 %
Temperature = 40 ° C

Time (hours)	Viscosity (cp) shear =1 (1/s)	Viscosity (cp) shear = 10 (1/s)	Viscosity (cp) shear = 40 (1/s)
0.0	196.6	137.62	137.62
0.5	196.6	157.28	157.28
1.5	196.6	176.94	176.94
3.0	393.2	135.92	216.26
6.0	393.2	314.56	289.99
9.0	786.4	511.16	417.78
12.0	786.4	511.16	417.78
20.0	786.4	511.16	417.78
24.0	983.0	668.44	604.55
27.0	983.0	688.10	614.29
30.0	1572.8	1199.16	948.6
33.0	1966.0	1336.88	1096.05

Table 5.7 : continue

39.0	3538.8	2634.44	2039.73
48.0	4521.8	3361.86	2521.40
54.0	12189.2	6979.30	4099.11
60.0	28703.6	14351.8	4915.0
72.0	196600.0	19660.0	4915.0

5.6- CORE FLOODING

The objective of the core flood experiments is to test the plugging effectiveness of the gel solution under reservoir conditions. The cores used in the flooding experiments were berea sandstone and limestone, some sandstone cores were fired to stabilize clay materials. The properties of core samples are shown in tables 5.8 and 5.9. The use of these two lithologies will demonstrate if there is a difference in the effectiveness of gel in plugging sandstone and limestone reservoirs. The experiments were carried out at 90 ° C with an overburden pressure of 2800.- 3000 psi. The plugging efficiency of the gel is demonstrated through permeability reduction and through the increase in the injection pressure.

A total of eight cores were; two cores were limestone and six were Berea sandstone. Three displacements were run on each core. The purpose of the first expriment was to measure the initial brine permeability. Then in the second run the gel was injected through the core until the gel solution was produced from the other side of the core. A total of 10.0 pore volume of gel solution was injected. A third run was used to measure the final permeability. A total of 24 coreflooding experiments were carried out.

The cores were first saturated with synthesized Arab-D brine. The cores were immersed in Arab-D brine inside transfer cell. The applied pressure in the transfer cell was 1000 psi. The composition of Arab-D brine is shown in table

5.10^{19} . The cores were flooded with Arab-D brine under reservoir conditions of temperature (90 ° C) and pressure (2800 psi - 3000 psi). The rate of injection was varied between 0.5 cc / min to 1.5 cc / min. A time of 5 minutes to 10 minutes was needed for pressure difference to stabilize.

The initial absolute permeability to Arab-D brine for each core was measured as shown in table 5.11. It was noted that if the steps required to measure the initial brine permeability for the same core, the seconed value of the permeability was less than the first value. This result might have been caused by some of the salt in the brine which has precipetated and occupied appendix C.some pore spaces leading to a lower value of permeabilitry. The composition of gel solution was 6.0 wt. % polyacrylamide, 0.2 wt. % chromium acetate and the concentrations of sodium lactate were 1.0 wt. %, 2.0 wt. % and 3.0 wt. %. For detail of coreflooding data see. To get a homogeneous gel solution, the gel solution was aged before flooding expriments. The displacement of Arab-D brine by gel solution was done under room temperature (≈ 25 ° C). injecting the gel solution under reservoir condition will plug the core setup lines and the end pieces, which will make it impossible to measure the permeability reductionin the core itself. After 10.0 pore volume of gel solutionwas injected, the cores were aged at atemperature of 90 ° C in the oven, while the corew setup lines and end pieceswere cleaned from the gel solution.

The pressure difference during gel injection was varied between 100 to 1300 psi at 1.5 cc / min. Permeability reduction was calculated as K_f / K_i (K_f is the final permeability and K_i is the initial permeability). The percentage of permeability reduction in the core tested varied between 92 % to 99.8 %. The results of the core flood experiments are shown in table 5.11. The formulated gel solution proved to be efficient in plugging the pores of the cores tested. This result are similar to what have been reported in literature[19].

Table 5.8 :Properties of core samples

Core number	Core type	Dry weight (gram)	Saturated weight (gram)	Pore volume Cm^3
1	sandstone	75.013	83.594	7.768
2	sandstone	72.379	81.513	8.269
3	sandstone	72.472	81.699	8.353
4	sandstone	74.634	84.349	8.795
5	sandstone (fired)	73.247	84.108	9.829
6	sandstone (fired)	73.632	84.732	10.397
7	Vuggy limestone	67.770	77.953	9.219
8	Vuggy limestone	68.085	77.604	8.619

Table 5.9 Properties of core samples

Core number	Length (Cm)	Diameter (Cm)	Bulk volume (Cm^3)	Pore volume (Cm^3)	Porosity (%)
1	7.50	2.53	37.704	7.768	20.60
2	7.22	2.53	36.297	8.269	22.78
3	7.23	2.53	36.347	8.353	22.98
4	7.46	2.53	37.503	8.795	23.45
5	7.46	2.53	37.503	9.829	26.21
6	7.50	2.53	37.704	10.397	27.58
20	7.39	2.47	35.410	9.219	26.04
21	7.46	2.40	33.748	8.619	25.54

Table 5.10 : Composition of Arab-D brine

Ions	Concentrations (mg / L)
Sodium	43800
Calcium	15400
Magnesium	1850
Salfate	510
Chloride	99500
Bicarbonate	290
Total; dissolved solids	161350

Table 5.11 : Results of core flood experiments

Core number	Initial permeability K_i (md)	Final permeability K_f (md)	Permeability reduction (%) 100 - (K_f /K_i) x100
1	237	2.4	98.99
2	395.	0.789	99.80
3	144	3.83	97.34
4	543.4	3.26	99.40
5	181	1.219	99.33
6	275	0.747	99.73
7	297	15.3	94.85
8	109.4	8.756	92.00

CHAPTER 6

CHAPTER 6

CONCLUSIONS And RECOMMENDATIONS

6.1- CONCLUSIONS

The following conclusions can be derived from this study of polyacrylamide chromium (III) acetate solution that involves the effect of retarder on gelation time, gel stability, gel solution viscosity and the effectiveness of gel in reducing the permeability of reservoir rocks.

1- In polyacrylamide / chromium (III) acetate solution,

A- The gelation time decreases as the concentration of polyacrylamide increases.

B- The gelation time increases as the concentration of chromium acetate increases.

C- The gelation time decreases as the temperature increases.

D- The gelation time increases as the concentration of sodium lactate increases.

2- A wide range of gelation time for the formulated gel (from days to months) can be obtained by increasing the concentration of the delaying agent or retarder (sodium lactate). Short gelation time is suitable for near wellbore treatments while long gelation time is suitable for fractured treatments.

3- The gel solution used in this satudy is an efficient plugging agent and can be formulated to produce a solid like material, and can be injected easily into the reservoir rocks..

4- During the period of this study (100 days) the formulated gel solution was found to be stable.

5- The viscosity of the gel solution decreases with increasing shear, but increases with increasing time and temperature.

6- The viscosity of the gel solution decreases as the concentration of the sodium lactate increases in the range studied.

6.2- RECOMMENDATIONS FOR FUTURE WORKS

The recommendations for future works that can be made from this study are as follows.

1- This study can be repeated in the future using different retarder types

2- It has been found that the stability of gel at low temperature (25° C and 60° C) is more than its stability at high temperature (90° C and 120° C). Is it the Oxygen that enhance the oxidation process leading to degelation or there is another effect from the temperature itself ?. these are the questions that should answered by future work or research, using sealed ampules after degassing.

3- The flow of the formulated gel in this study can be tested in fractures and sandpacks

4- An important topic for future research is the phase stability of the formulated gel with Arab-D brine at the reservoir conditions.

REFERENCES

1. Terry, Ronald E. "Correlation of Gelation Times for Polymer Solutions Used as Sweep Improvement Agent." Society of Petroleum Engineers of AIME. Houston, Texas. April 1981 pp. 229-235.

2. Jordan, Deborab S. Et. Al. "The Effect of Temperature on Gelation Time for Polyacrylamide Chromium (III) Systems." SPE 10059. SPE and AIME 56 Annual Fall Technical Conference and Exhibition., San Antonio, Texas, Oct. 5-7, 1981 pp. 1-11.

3. Huang, Chy-Gang et.al. "An Experimental Study of the In-Situ Gelation of Chromium (+3)/Polyacrylomide Polymer In Porous Media." SPE Reservoir Engineering, No. 1988 pp. 583-592.

4. Sydansk, R.D. "A New Conformance-Improvement-Treatment Chromium (III) Gel Technology." SPE/DOE 17329. SPE/DOE Enhanced Oily Recovery Symposium, Tulsa, Oklahoma, April 17-20, 1988, pp. 99-114.

5. Purkaple, J.D. and Summers, L.E., "Evolution Of Commercial Crosslinked Polyacrylamide Gel Systems For Injection Profile Modification." SPE/DOE 17331. SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, April 17029, 1988, pp. 125-135.

6. Morodi-Aroghi, A. Et. Al. "Thermally Stable Gels for Near-Wellfore Permeability Contrast Corrections." SPE 18500, SPE International Symposium on Oil Field Chemistry. Houston, Texas, Feb. 8-10, 1989. pp. 367-378.

7. Marty, L. And Willhite, G.P. "The Effect of Flow-Rate on the In-Situ Gelation of a Chrome/Redox/Polyacrylamide System." PE 18504. SPE International Symposium on Oil Field Chemistry, Houston, Texas. Feb. 8-10, 1989, pp. 415-424.

8. Sydansk, R.D. "Acrylomide-Polymers/Chromium (III)- Carboxylate Gels For Near Wellbore Matrix Treatments." SPE/DOE 20214. SPE/DOE Seventh Symposium on Enhanced Oil Recovery. Tulsa, Oklahoma, April 22-25, 1990, 397-408.

9. Tood, B. J. Et. Al. " A mathematical Model of In-Situ Gelation of Polyacrylamide by Redox Process." SPE/DOE 20215. SPE/DOE Seventh Symposium on Enhanced Oil Recovery. Tulsa, Oklahoma, 1990, pp. 409-419.

10. Lockhart, T. P. 'Chemical and Structural Studies on Cr^{+3}/Polyacrylamide Gels." SPE 20998. SPE International Symposium on Oil Field Chemistry, Anaheim, California, Feb., 20-24, 1995. pp. 13-24.

11. Seright, R.S. "Impact of Permeability and Liothology on Gel Performance." SPE/DOE 24190. SPE/DOE Eight Symposium on

Enhanced Oil Recovery. Tulsa, Oklahoma, April 22-24, 1992, pp. 347-357.

12. Lockhart, T.P. and Albonico Paola. " A New Gelation Technology for In-Depth Placement of Cr^{+3}/Polymer Gels in High Temperature Reservoir." SPE/DOE 24194. SPE/DOE Eight Symposium on Enhanced Oil Recovery. Tulsa, Oklahoma, April 22-24, 1990, 397-408.

13. H. Sun, J. Liang and Seright, R.S. "Reduction of Oil and Water Permeabilities Using Gels." SPE/DOE 24195. SPE/DOE Eight Symposium on Enhanced Oil Recovery. Tulsa, Oklahoma, April 22-24, 1992, 409-418.

14. Albonico, paola; Burrafato, Giovanni; Di Lullo, Alberto and Lockhart, T.P. "Effective Gelation-Deloying Additives for Cr^{+3}/Polymer Gels." SPE 25221. SPE International Symposium on Oil field Chemistry, New Orleans, LA., USA, March 2-5, 1993, pp. 667-680.

15. Seright. R. S. "Gel Placement In Fractured Systems." SPE/DOE 27740. SPE/DOE Ninth Symposium on Improved Oil Recovery. Tulsa, Oklahoma, April 17-20, 1994, pp. 19-20.

16. Southwell, G.P. and Posey, S.M. "Application and Result of Acrylamide-Polymer/Chromium (III) Carboxylate Gels." SPE/DOE 27779. SPE/DOE Ninth Symposium on Improved Oil Recovery. Tulsa, Oklahoma, April 17-20, 1994, pp. 513-526

17. Barlosek, Martin et. Al. "Polymer Gels For Conformance Treatments: Propagation of Cr(III) Crosslinking Complexes In Porous Media." SPE/DOE 27827. SPE/DOE Ninth Symposium on Improved Oil Recovery. Tulsa, Oklahoma, April 17-20, 1994, pp. 505-517.

18. Liang, Jenn-Tai et.al. "why Do Gels Reduce Water Permeability More Than oil Permeability? " SPE/DOE 27829. SPE/DOE Seventh Symposium on Enhanced Oil Recovery. Tulsa, Oklahoma, April 17-20, 1994, 519-528.

19. Naser-El-Din, H.A. "Design of A Water Shut-Off Treatment For Producing Wells in Saudi Arabia." 2nd International Conference on Chemistry In Industry, Saudi Arabian International Chemical Sciences Chapter of American Chemical Society and Bahrain Society of Chemists, Manama, Bahrain, Oct. 24-26, 1994, 170-188

20. Lackhart, , T.P. and Albonic Paola "New Chemistry For the Placement of Chromium (III)/ Polymer Gels In High-Temperature Reservoirs." SPE Production and Facilities, Nov. 1994- pp. 273-279.

21. Mohammed, M. A. And Al-Majed, A.A. "A Study of Factor Affecting Gelation Time of Polyacrlamide/Chromium(VI) System." Saudi Arabian Journal of Technology, Fall/Winter, 1994 pp. 26-32.

APPENDICES

APPENDIX A

APPENDIX A

CALCULATIONS EXAMPLES

Calculation Example # 1

The purpose of this example is to show how the weight of each chemical in the gel solution is calculated from an assigned concentration of each chemical.

If the concentration of the solution required are

Polyacrylamide concentration = 6.0 %

Chromium acetate concentration = 0.2 %

Sodium lactate concentration = 3.0 %

and the weight of the solution is 15.0 g then

polyacylamide weight = (6.0 / 100) x 15.0
= 0.9 g

chromium acetate weight = (0.2 / 100) x 15
= 0.03 g

sodium lactate weight = (3.0 / 100) x 15
= 0.45 g

The weight of each chemical that are mixed in the solution are

weight of polyacrylamide solution = (100 / 15) x 0.9
= **6.0 g**

Where 15 is % by weight of the polymer

weight of chromium acetate solution = (100 / 11.5) x 0.03
= **0.261 g**

Where 11.5 is % by weight of chromium acetate

weight of sodium lactate solution = (100 / 60) x 0.45
= **0.75**

Where 60 is % by weight of sodium lactate

Weight of water added = 15-0 - 6.0 - 0.261 - 0.75
= **7.989 g**

Calculated Example # 2

The following calculations show how Arab-D brine is synthesized.

Arab-D brine consists from the following :

Composition of Arab-D brine

Ions	Concentrations (mg / L)
Sodium	43800
Calcium	15400
Magnesium	1850
Salfate	510
Chloride	99500
Bicarbonate	290
Total; dissolved solids	161350

Ioni concentration (g / L) (1)	Molar mass of ion (2)	Number of moles / L (1) / (2)
43.800 Na^{+}	**22.99**	1.905
15.400 Ca^{2+}	**40.05**	0.385
1.850 Mg^{2+}	**24.31**	0.0761
0.510 So_4^{2-}	**96.06**	0.00531
0.290 Hco_3^{-}	**61.0**	0.00475

The above ions are found in the following compunds

Compoumds	Total molar mass (g) (1)	Number of moles / L (2)	Weight of compound to be mixed / L (1) x (2)
Sodium choloride	58.44	1.905	**111.328**
Calcium choloride .	110.98	0.385	**42.720**
Magnesium choloride-$6H_2o$	203.33	0.0761	**15.473**
Sodium Salfate	142.04	0.00531	**0.754**
Sodium Bicarbonate	83.99	0.00475	**0.3995**

Calculated Example # 3

This example shows how the gel solution viscosity is caculated using the conversion factor and display reading from Wells Broockfield viscometer.

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.0	1966.00	1966.0
1.0	2	1.7	983.00	1671.1
2.5	5	3.7	393.20	1454.84
5	10	6.8	196.60	1336.88
10	20	12.5	98.30	1228.75
20	40	22.3	49.15	1096.05
50	100	45.7	19.66	898.46
100	200	74.8	9.83	735.28

APPENDIX B

APPENDIX B

GELATION TIME MEASUREMENTS

Table 1: Gelation time measurement

Temperature = room temperature (≈ 25 ° C)
Polyacrylamide concentration = 2.0 %
Chromium acetate concentration = 0.5 %

TIME	CODE
1 Hour	A
2.5	A
4	A
6	A
8	A
10	A
12	A
14	A
24	A
48	A
3 days	A
4	A
6	A
10	A
14	A
15	A
16	A
18	A
20	A
21	A
22	A
24	A
:	A

Table 2 : Gelation time measurement

Temperature = room temperature (25 ° C)
Polyacrylamide concentration = 5.00 %
Chromium acetate concentration = 0.25 %

TIME	CODE
1 hour	A
2.5	A
4	A
6	A
8	A
10	A
12	A
14	A
24	A
24	A
3 days	A
4	A
6	A
10	A
14	C
15	F
16	G
18	G
20	H
21	H
22	H
24	I
:	I
:	I

Table 3 : Gelation time measurement

Temperature = room temperature (25 ° C)
Polyacrylamide concentration = 8.00 %
Chromium acetate concentration = 0.125 %

TIME	CODE
1 hour	A
2.5	A
4	A
6	A
8	A
10	A
12	A
14	\A
24	A
24	A
72	B
83	C
96	H
100	H
107	I
6 days	I
10	I
14	I
15	I
16	I
18	I
20	I
:	I
:	I

Table 4 : Gelation time measurement

Temperature = room temperature (25 ° C)
Polyacrylamide concentration = 10.000 %
Chromium acetate concentration = 0.125 %

TIME	CODE
1 hour	**A**
3	**A**
5	**A**
7	**A**
9	**B**
11	**B**
21	**C**
48	**D**
57	**D**
69	**H**
80	**I**
4 days	**I**
6	**I**
10	**I**
14	**I**
15	**I**
16	**I**
17	**I**
18	**I**
20	**I**
21	**I**
22	**I**
:	**I**
:	**I**

Table 5 : Gelation time measurement

Temperature = room temperature (25 ° C)
Polyacrylamide concentration = 12.000 %
Chromium acetate concentration = 0.125 %

TIME	CODE
0.5 hour	**A**
1	**A**
5.5	**A**
7.5	**A**
9.5	**B**
11.5	**B**
13.5	**B**
23.5	**D**
48	**I**
3 days	**I**
3.5	**I**
4	**I**
6	**I**
10	**I**
14	**I**
15	**I**
16	**I**
17	**I**
18	**I**
20	**I**
21	**I**
22	**I**
:	**I**
:	**I**

Table 6 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 2.0 %
Chromium acetate concentration = 0.5 %

TIME	CODE
1 hour	A
1.5	A
2.5	A
3	A
4	A
5	A
14	A
25	A
2 days	A
3	A
5	A
8	A
11	B
12	C
13	E
15	F
17	G
23	H
33	I
34	J
37	J
40	J
:	J
:	J

Table 7 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 5.0 %
Chromium acetate concentration = 0.25 %

TIME	CODE
1 hour	**A**
1.5	**A**
2.5	**B**
3	**C**
4	**G**
5	**I**
6	**J**
25	**J**
2 days	**J**
3	**J**
5	**J**
8	**J**
11	**J**
12	**J**
13	**J**
15	**J**
17	**J**
23	**J**
33	**J**
35	**J**
37	**J**
40	**J**
:	**J**
:	**J**

Table 8 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 8.0 %
Chromium acetate concentration = 0.125 %

TIME	CODE
0.5 hour	**A**
1	**A**
2	**E**
2.5	**H**
3	**I**
4	**J**
6	**J**
25	**J**
2 days	**J**
3	**J**
5	**J**
8	**J**
11	**J**
12	**J**
13	**J**
15	**J**
17	**J**
23	**J**
33	**J**
35	**J**
37	**J**
40	**J**
:	**J**
:	**J**

Table 9 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 10.00 %
Chromium acetate concentration = 0.125 %

TIME	CODE
0.5 hour	A
1	A
2	I
3	J
4	J
5	J
6	J
25	J
2 days	J
3	J
5	J
8	J
11	J
12	J
13	J
15	J
17	J
23	J
33	J
35	J
37	J
40	J
:	J
:	J

Table 10 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 12.00 %
Chromium acetate concentration = 0.125 %

TIME	CODE
0.5 hour	A
1	B
2	I
3	J
4	J
5	J
6	J
25	J
2 days	J
3	J
5	J
8	J
11	J
12	J
13	J
15	J
17	J
23	J
33	J
35	J
37	J
40	J
:	J
:	J

Table 11 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 2.0 %
Chromium acetate concentration = 0.5 %
Sodium lactate concentration = 5.0 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
60	A
70	A
80	A
115	G
120	I
:	I
:	I

Table 12 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 5.00 %
Chromium acetate concentration = 0.25 %
Sodium lactate concentration = 5.00 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
60	F
65	G
70	I
100	I
120	I
:	I
:	I

Table 13 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 8.000 %
Chromium acetate concentration = 0.125 %
Sodium lactate concentration = 5.000 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
60	F
70	G
80	I
100	I
120	I
:	I
:	I

Table 14 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 10.00 %
Chromium acetate concentration = 0.125 %
Sodium lactate concentration = 5.000 %

TIME	CODE
4 hour	**A**
6	**A**
8	**A**
10	**A**
15	**A**
25	**A**
35	**A**
45	**A**
2 days	**A**
6	**A**
8	**A**
10	**A**
15	**A**
20	**A**
25	**A**
40	**A**
50	**A**
70	**F**
80	**G**
95	**I**
100	**I**
120	**I**
:	**I**
:	**I**

Table 15 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 12.00 %
Chromium acetate concentration = 0.125 %
Sodium lactate concentration = 5.000 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
55	A
60	E
85	I
100	I
120	I
:	I
:	I

Table 16 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 2.0 %
Chromium acetate concentration = 0.5 %
Sodium lactate concentration = 10.0 %

TIME	CODE
4 hour	**A**
6	**A**
8	**A**
10	**A**
15	**A**
25	**A**
35	**A**
45	**A**
2 days	**A**
6	**A**
8	**A**
10	**A**
15	**A**
20	**A**
25	**A**
40	**A**
50	**A**
55	**A**
60	**E**
85	**I**
100	**I**
120	**I**
:	**I**
:	**I**

Table 17 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 5.00 %
Chromium acetate concentration = 0.25 %
Sodium lactate concentration = 10.0 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
55	A
60	E
85	I
100	I
120	I
:	I
:	I

Table 18 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 8.000 %
Chromium acetate concentration = 0.125 %
Sodium lactate concentration = 10.000 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
55	A
60	E
85	I
100	I
120	I
:	I
:	I

Table 19 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 10.000 %
Chromium acetate concentration = 0.125 %
Sodium lactate concentration = 10.000 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
55	A
60	E
85	I
100	I
120	I
:	I
:	I

Table 20 : Gelation time measurement

Temperature = 60 ° C
Polyacrylamide concentration = 12.000 %
Chromium acetate concentration = 0.125 %
Sodium lactate concentration = 10.000 %

TIME	CODE
4 hour	A
6	A
8	A
10	A
15	A
25	A
35	A
45	A
2 days	A
6	A
8	A
10	A
15	A
20	A
25	A
40	A
50	A
55	A
60	E
85	I
100	I
120	I
:	I
:	I

Table 21 : Gelation time measurement

Temperature = room temperature (25 °C)
Polyacrylamide concentration = 5.0 %
Chromium acetate concentration = 0.5 %

TIME	CODE
1 day	**A**
2	**A**
3	**A**
6	**A**
9	**A**
14	**A**
22	**B**
32	**C**
42	**D**
48	**F**
89	**G**
340	**I**

Table 22 : Gelation time measurement

Temperature = room temperature (25 °C)
Polyacrylamide concentration = 5.000 %
Chromium acetate concentration = 0.125 %

TIME	CODE
1 day	**A**
2	**A**
3	**A**
6	**B**
9	**D**
10	**E**
11	**F**
12	**G**
13	**G**
14	**H**
16	**I**
20	**I**
30	**I**
35	**I**
40	**I**
45	**I**
50	**I**
55	**I**
60	**I**
85	**I**
100	**I**
120	**I**
:	**I**
:	**I**

Table 23 : Gelation time measurement

Temperature = 60 °C
Polyacrylamide concentration = 5.00 %
Chromium acetate concentration = 0.50 %

TIME	CODE
1 hour	**A**
1.5	**B**
2	**D**
2.5	**E**
4	**E**
5	**F**
6	**F**
7	**G**
8	**G**
10	**G**
14	**G**
22	**G**
26	**H**
31	**H**
33	**I**
45	**I**
50	**I**
55	**I**
60	**I**
85	**I**
100	**I**
120	**I**
:	**I**
:	**I**

Table 24 : Gelation time measurement

Temperature = 60 °C
Polyacrylamide concentration = 5.000 %
Chromium acetate concentration = 0.125 %

TIME	CODE
0.5 hour	**A**
1	**B**
1.5	**I**
3	**J**
4	**J**
5	**J**
6	**J**
7	**J**
8	**J**
10	**J**
14	**J**
22	**J**
26	**J**
31	**J**
33	**J**
45	**J**
50	**J**
55	**J**
60	**J**
85	**J**
100	**J**
120	**J**
:	**J**
:	**J**

Table 25 : Gelation time measurement

Temperature = 60 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0 %

TIME	CODE
1 hour	A
2	A
2.5	A
3	A
4	A
5	A
6	A
7	A
8	A
12	A
24	A
48	A
69	A
3 days	A
5	A
7	A
10	A
12	C
13	G
14	H
15	I
16	J
:	J
:	J

Table 26 : Gelation time measurement

Temperature = 60 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0 %

TIME	CODE
1 hour	A
2	A
2.5	A
3	A
4	A
5	A
6	A
7	A
8	A
12	A
24	A
48	A
69	A
3 days	A
7	F
8	H
9	I
10	J
13	J
14	J
15	J
16	J
:	J
:	J

Table 27 : Gelation time measurement

Temperature = 60 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0 %

TIME	CODE
1 hour	A
2	A
2.5	A
3	A
4	A
5	A
6	A
7	A
8	A
12	A
24	A
40	B
48	D
60	E
69	G
75	H
79	H
85	I
88	J
90	J
95	J
100	J

Table 27 : Gelation time measurement

Temperature = 60 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %

TIME	CODE
0.5 hour	**A**
1	**D**
1.5	**I**
3	**J**
4	**J**
5	**J**
6	**J**
7	**J**
8	**J**
12	**J**
24	**J**
40	**J**
48	**J**
60	**J**
69	**J**
75	**J**
79	**J**
85	**J**
88	**J**
90	**J**
::	

Table 32 : Gelation time measurement

Temperature = 90 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %

TIME	CODE
0.5 hour	**A**
0.75	**D**
1	**E**
1.25	**G**
1.5	**I**
2	**I**
6	**I**
7	**I**
8	**I**
12	**I**
15	**I**
20	**I**
24	**I**
1 days	**I**
5	**I**
10	**I**
15	**I**
20	**I**
25	**I**
30	**I**
::	

Table 33 : Gelation time measurement

Temperature = 90 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0 %

TIME	CODE
1 hour	**A**
3	**A**
5	**A**
9	**A**
12	**C**
16	**D**
20	**E**
24	**E**
30	**G**
34	**G**
38	**H**
42	**H**
45	**I**
1 days	**I**
5	**I**
10	**I**
15	**I**
20	**I**
25	**I**
30	**I**

Table 34 : Gelation time measurement

Temperature = 90 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0 %

TIME	CODE
1 hour	A
3	A
5	A
9	A
12	A
16	A
20	A
24	A
30	A
34	A
38	A
42	A
45	A
1 days	A
2	A
`3	F
3.5	G
3.75	H
4	I
5	I
10	I
15	I
20	I
25	I
30	I

Table 35 : Gelation time measurement

Temperature = 90 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0 %

TIME	CODE
1 hour	A
4	A
8	A
12	A
20	A
24	A
30	A
40	A
1 day	A
2	A
3	A
4	A
4.5	B
5	E
5.5	F
5.75	F
6	G
6.25	H
6.5	I
7	I
10	I
15	I
20	I
25	I
30	I

Table 36 : Gelation time measurement
Temperature = 120 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %

TIME	CODE
0.5 hour	I
2	I

Table 37 : Gelation time measurement
Temperature = 120 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0 %

TIME	CODE
0.5 hour	A
1	A
2.5	H
2	I

Table 38 : Gelation time measurement
Temperature = 120 °C
Polyacrylamidee concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0 %

TIME	CODE
0.5 hour	A
1	A
2	A
2.5	A
3	B
4	C
5	E
5.5	F
6	I

Table 39 : Gelation time measurement

Temperature = 120 °C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0 %

TIME	CODE
0.5 hour	A
1	A
2	A
3	A
4	A
5	A
6	A
7	C
8	F
8.5	G
9	I
10	I
11	I
12	I

APPENDIX C

APPENDIX C

GEL VISCOSITY MEASUREMENTS

Table 44 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.3	393.20	117.96
5	10	0.6	196.60	117.96
10	20	1.1	98.30	108.13
20	40	2.2	49.15	108.13
50	100	5.2	19.66	102.23
100	200	9.8	9.83	96.33

Table 45 Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium Lactate concentration = 1.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.3	393.20	117.96
5	10	0.6	196.60	117.96
10	20	1.1	98.30	108.13
20	40	2.2	49.15	108.13
50	100	5.2	19.66	102.23
100	200	10.0	9.83	98.30

Table 46 Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.3	393.20	117.96
5	10	0.6	196.60	117.96
10	20	1.2	98.30	117.96
20	40	2.3	49.15	113.05
50	100	5.6	19.66	110.10
100	200	10.7	9.83	105.18

Table 47 Gel viscosity measurement

Temperature = 40 ° C
Polymer concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.7	196.60	137.62
10	20	1.3	98.30	127.79
20	40	2.6	49.15	127.79
50	100	6.2	19.66	121.89
100	200	12.0	9.83	117.96

Table 48 Gel viscosity measurement

Temperature = 40 ° C
Polymer concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 6.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.5	393.20	196.6
5	10	1.0	196.60	196.6
10	20	2.0	98.30	196.6
20	40	3.9	49.15	191.69
50	100	9.7	19.66	190.70
100	200	18.0	9.83	176.94

Table 49 Gel viscosity measurement
Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 9.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.4	983.00	393.2
2.5	5	0.8	393.20	314.56
5	10	1.6	196.60	314.56
10	20	3.0	98.30	294.90
20	40	5.6	49.15	275.24
50	100	12.9	19.66	253.61
100	200	24.5	9.83	240.84

Table 50 Gel viscosity measurement
Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 12.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.3	1966.00	589.8
1.0	2	0.6	983.00	589.8
2.5	5	1.2	393.20	471.84
5	10	2.4	196.60	471.84
10	20	4.5	98.30	442.35
20	40	8.5	49.15	417.78
50	100	18.9	19.66	371.57
100	200	33.8	9.83	332.25

Table 51 Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 15.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.4	1966.00	786.4
1.0	2	0.6	983.00	589.8
2.5	5	1.5	393.20	589.8
5	10	2.8	196.60	550.48
10	20	5.3	98.30	520.99
20	40	10.0	49.15	491.50
50	100	22.3	19.66	438.42
100	200	38.8	9.83	381.40

Table 52 Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 20.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.6	1966.00	1179.6
1.0	2	1.1	983.00	1081.3
2.5	5	2.6	393.20	1022.32
5	10	4.8	196.60	943.68
10	20	9.0	98.30	884.70
20	40	16.3	49.15	801.15
50	100	34.4	19.66	676.30
100	200	56.7	9.83	557.36

Table 53 Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 24.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.0	1966.00	1966.6
1.0	2	1.9	983.00	1867.7
2.5	5	4.4	393.20	1730.08
5	10	8.1	196.60	1592.46
10	20	14.8	98.30	1454.84
20	40	25.3	49.15	1243.50
50	100	48.4	19.66	951.44
100	200	75.2	9.83	739.23

Table 54 Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 27.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.6	1966.00	3145.6
1.0	2	2.9	983.00	2850.7
2.5	5	6.5	393.20	2555.8
5	10	11.7	196.60	2300.22
10	20	20.5	98.30	2015.15
20	40	34.1	49.15	1676.02
50	100	61.2	19.66	1203.19
100	200	94.9	9.83	932.87

Table 55 Gel viscosity measurement
Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 30.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	2.9	1966.00	5701.4
1.0	2	5.1	983.00	5013.3
2.5	5	11.8	393.20	4639.76
5	10	18.6	196.60	3656.76
10	20	29.8	98.30	2929.34
20	40	46.7	49.15	2295.31
50	100	83.3	19.66	1637.68
100	200	> 100	9.83	> 983.0

Table 56 Gel viscosity measurement
Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 33.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	8.4	1966.00	16514.4
1.0	2	10.7	983.00	10518.1
2.5	5	21.7	393.20	8532.44
5	10	26.5	196.60	5209.90
10	20	41.2	98.30	4049.96
20	40	62.7	49.15	3081.71
50	100	>100	19.66	> 1966.00
100	200	> 100	9.83	> 983.0

Table 57 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.3	393.20	117.96
5	10	0.6	196.60	117.96
10	20	1.1	98.30	108.13
20	40	2.1	49.15	103.22
50	100	5.1	19.66	100.27
100	200	9.8	9.83	96.33

Table 58 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium asetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.5	393.20	196.6
5	10	0.8	196.60	157.28
10	20	1.6	98.30	157.28
20	40	3.2	49.15	157.28
50	100	7.0	19.66	137.62
100	200	12.7	9.83	124.84

Table 59 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.3	983.00	294.9
2.5	5	0.7	393.20	275.24
5	10	1.1	196.60	216.26
10	20	2.1	98.30	206.43
20	40	4.1	49.15	201.52
50	100	8.4	19.66	165.14
100	200	15.1	9.83	148.43

Table 60 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.6	1966.00	1179.6
1.0	2	1.0	983.00	983.0
2.5	5	1.8	393.20	707.76
5	10	2.6	196.60	511.16
10	20	4.1	98.30	403.03
20	40	6.1	49.15	299.82
50	100	11.2	19.66	220.19
100	200	18.5	9.83	181.86

Table 61 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 6.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.0
100	200	> 100	9.83	> 983.0

Table 62 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.2	983.00	196.6
2.5	5	0.5	393.20	196.6
5	10	0.8	196.60	157.28
10	20	1.4	98.30	137.62
20	40	2.5	49.15	122.88
50	100	5.7	19.66	112.06
100	200	9.9	9.83	97.32

Table 63 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 1.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.0
100	200	> 100	9.83	> 983.0

Table 64 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.7	196.60	137.62
10	20	1.3	98.30	127.79
20	40	2.7	49.15	122.88
50	100	5.8	19.66	114.03
100	200	11.2	9.83	110.10

Table 65 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.7	196.60	137.62
10	20	1.3	98.30	127.79
20	40	2.7	49.15	122.88
50	100	6.1	19.66	119.93
100	200	11.7	9.83	115.01

Table 66 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.8	196.60	157.28
10	20	1.4	98.30	137.62
20	40	2.8	49.15	137.62
50	100	6.7	19.66	131.72
100	200	12.8	9.83	125.83

Table 66 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.5	393.20	196.6
5	10	1.0	196.60	196.6
10	20	1.9	98.30	186.77
20	40	3.6	49.15	176.94
50	100	8.5	19.66	167.11
100	200	15.9	9.83	156.30

Table 67 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 6.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.3	1966.00	589.8
1.0	2	0.4	983.00	393.2
2.5	5	0.8	393.20	314.56
5	10	1.5	196.60	294.90
10	20	2.9	98.30	285.07
20	40	5.6	49.15	275.24
50	100	12.5	19.66	245.75
100	200	23.2	9.83	228.06

Table 68 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 9.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.4	1966.00	786.4
1.0	2	0.6	983.00	589.8
2.5	5	1.2	393.20	471.84
5	10	2.3	196.60	452.18
10	20	4.4	98.30	432.52
20	40	8.5	49.15	417.78
50	100	17.2	19.66	338.15
100	200	32.6	9.83	320.46

Table 69 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 12.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.4	1966.00	786.4
1.0	2	0.6	983.00	589.8
2.5	5	1.3	393.20	511.16
5	10	2.6	196.60	511.16
10	20	5.1	98.30	501.33
20	40	10.2	49.15	501.33
50	100	21.5	19.66	422.69
100	200	38.1	9.83	374.52

Table 70 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 15.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.6	1966.00	1179.6
1.0	2	1.0	983.00	983.0
2.5	5	2.2	393.20	865.04
5	10	4.0	196.60	786.40
10	20	7.5	98.30	737.25
20	40	13.7	49.15	673.36
50	100	29.2	19.66	574.07
100	200	51.2	9.83	503.30

Table 71 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 20.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.0	1966.00	1966.0
1.0	2	1.5	983.00	1474.5
2.5	5	3.3	393.20	1297.56
5	10	6.0	196.60	1179.60
10	20	11.2	98.30	1100.96
20	40	19.7	49.15	968.26
50	100	39.9	19.66	772.64
100	200	64.2	9.83	631.09

Table 72 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 24.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.0	1966.00	1966.0
1.0	2	1.8	983.00	1769.40
2.5	5	4.4	393.20	1730.08
5	10	8.2	196.60	1612.12
10	20	14.7	98.30	1445.01
20	40	25.8	49.15	1268.07
50	100	50.7	19.66	996.76
100	200	80.6	9.83	792.30

Table 73 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 27.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	2.0	1966.00	3932.00
1.0	2	3.4	983.00	3342.20
2.5	5	7.8	393.20	3066.96
5	10	13.8	196.60	2713.08
10	20	23.6	98.30	2319.88
20	40	39.7	49.15	1951.26
50	100	74.4	19.66	1462.70
100	200	> 100	9.83	> 983

Table 74 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 33.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	2.6	1966.00	5111.6
1.0	2	4.7	983.00	4620.10
2.5	5	9.3	393.20	3656.76
5	10	15.8	196.60	3106.28
10	20	27.4	98.30	2693.42
20	40	43.3	49.15	2128.20
50	100	84.2	19.66	1655.37
100	200	> 100	9.83	> 983.0

Table 75 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 39.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	4.1	1966.00	8650.40
1.0	2	7.1	983.00	6979.30
2.5	5	14.9	393.20	5858.68
5	10	24.8	196.60	4875.68
10	20	40.2	98.30	3951.66
20	40	62.8	49.15	3086.62
50	100	> 100	19.66	> 1966.00
100	200	> 100	9.83	> 983

Table 76 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 48.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	7.7	1966.00	15138.20
1.0	2	13.4	983.00	13172.20
2.5	5	26.8	393.20	10537.76
5	10	43.6	196.60	8571.76
10	20	67.6	98.30	6645.08
20	40	> 100	49.15	> 4915.00
50	100	> 100	19.66	> 1966.00
100	200	> 100	9.83	> 983

Table 77 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.2
2.5	5	0.3	393.20	117.96
5	10	0.5	196.60	98.3
10	20	0.9	98.30	88.47
20	40	1.7	49.15	83.56
50	100	4.2	19.66	82.57
100	200	8.3	9.83	81.59

Table 78 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.4	983.00	393.2
2.5	5	0.7	393.20	275.24
5	10	0.8	196.60	157.28
10	20	1.4	98.30	137.62
20	40	2.4	49.15	117.96
50	100	5.3	19.66	104.20
100	200	10.2	9.83	100.27

Table 79 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.3	1966.00	589.8
1.0	2	0.6	983.00	589.8
2.5	5	0.9	393.20	353.88
5	10	1.2	196.60	235.92
10	20	1.6	98.30	157.28
20	40	2.6	49.15	127.79
50	100	5.8	19.66	114.03
100	200	10.8	9.83	106.16

Table 80 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.3	1966.00	589.8
1.0	2	0.6	983.00	589.8
2.5	5	0.9	393.20	353.88
5	10	1.2	196.60	235.92
10	20	1.6	98.30	157.28
20	40	2.6	49.15	127.79
50	100	5.8	19.66	114.03
100	200	11.4	9.83	112.06

Table 81 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Lactate concentration = 2.0
Time (hours) = 6.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.0
100	200	> 100	9.83	> 983.0

Table 82 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.3	393.20	117.96
5	10	0.6	196.60	117.96
10	20	1.1	98.30	108.13
20	40	1.7	49.15	83.56
50	100	3.5	19.66	68.81
100	200	6.3	9.83	61.92

Table 83 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.3	393.20	117.96
5	10	0.6	196.60	117.96
10	20	1.1	98.30	108.13
20	40	1.7	49.15	83.56
50	100	2.7	19.66	53.08
100	200	4.6	9.83	45.23

Table 84 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 2.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.0
100	200	> 100	9.83	> 983.0

Table 85 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0 %
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.7	196.60	137.62
10	20	1.4	98.30	137.62
20	40	2.8	49.15	137.62
50	100	6.7	19.66	131.72
100	200	12.9	9.83	126.81

Table 86 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.8	196.60	157.28
10	20	1.6	98.30	157.28
20	40	3.2	49.15	157.28
50	100	7.5	19.66	147.45
100	200	13.5	9.83	132.71

Table 87 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.5	393.20	196.6
5	10	0.9	196.60	176.94
10	20	1.8	98.30	176.94
20	40	3.6	49.15	176.94
50	100	9.3	19.66	176.94
100	200	15.4	9.83	151.38

Table 88 : Gel viscosity measurement

Temperature = 40 ° C
Polyaccrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.3	983.00	294.9
2.5	5	0.7	393.20	275.24
5	10	1.2	196.60	235.92
10	20	2.3	98.30	226.09
20	40	4.4	49.15	216.26
50	100	10.1	19.66	198.57
100	200	19.0	9.83	186.77

Table 89 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 6.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.4	983.00	393.2
2.5	5	0.8	393.20	314.56
5	10	1.6	196.60	314.56
10	20	3.1	98.30	304.73
20	40	5.9	49.15	289.99
50	100	13.5	19.66	265.41
100	200	24.2	9.83	237.89

Table 90 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 9.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.4	1966.00	786.4
1.0	2	0.6	983.00	589.8
2.5	5	1.3	393.20	511.16
5	10	2.6	196.60	511.16
10	20	4.6	98.30	452.18
20	40	8.5	49.15	417.78
50	100	19.1	19.66	375.51
100	200	33.7	9.83	331.27

Table 91 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 12.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.4	1966.00	786.4
1.0	2	0.6	983.00	589.8
2.5	5	1.3	393.20	511.16
5	10	2.6	196.60	511.16
10	20	4.6	98.30	452.18
20	40	8.5	49.15	417.78
50	100	19.2	19.66	377.47
100	200	34.1	9.83	335.20

Table 92 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 15.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.6	1966.00	1179.6
1.0	2	0.9	983.00	884.7
2.5	5	2.2	393.20	865.04
5	10	3.9	196.60	766.74
10	20	7.3	98.30	717.59
20	40	13.4	49.15	658.61
50	100	27.4	19.66	538.68
100	200	47.3	9.83	464.96

Table 93 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 20.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.4	1966.00	786.4
1.0	2	0.6	983.00	589.8
2.5	5	1.4	393.20	550.48
5	10	2.6	196.60	511.16
10	20	5.1	98.30	501.33
20	40	8.5	49.15	417.78
50	100	21.7	19.66	426.62
100	200	38.4	9.83	377.47

Table 94 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 24.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.5	1966.00	983.0
1.0	2	0.8	983.00	786.4
2.5	5	1.9	393.20	747.08
5	10	3.4	196.60	668.44
10	20	6.3	98.30	619.29
20	40	12.3	49.15	604.55
50	100	25.6	19.66	503.30
100	200	43.5	9.83	427.61

Table 95 : Gel viscosity measurement

Temperature = 40 ° C
Polyaccrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 27.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.5	1966.00	983.0
1.0	2	0.8	983.00	786.4
2.5	5	1.9	393.20	747.08
5	10	3.5	196.60	688.10
10	20	6.6	98.30	648.78
20	40	12.6	49.15	619.29
50	100	26.6	19.66	522.96
100	200	46.2	9.83	454.15

Table 96 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 30.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.8	1966.00	1572.8
1.0	2	1.5	983.00	1474.5
2.5	5	3.2	393.20	1258.24
5	10	6.1	196.60	1199.26
10	20	10.8	98.30	1061.64
20	40	19.3	49.15	948.60
50	100	39.2	19.66	770.67
100	200	63.4	9.83	623.22

Table 97 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 33.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.0	1966.00	1966.0
1.0	2	1.7	983.00	1671.1
2.5	5	3.7	393.20	1454.84
5	10	6.8	196.60	1336.88
10	20	12.5	98.30	1228.75
20	40	22.3	49.15	1096.05
50	100	45.7	19.66	898.46
100	200	74.8	9.83	735.28

Table 98 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 39.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.8	1966.00	3538.8
1.0	2	3.2	983.00	3245.6
2.5	5	7.5	393.20	2949.0
5	10	13.4	196.60	2634.44
10	20	24.2	98.30	2378.86
20	40	41.5	49.15	2039.73
50	100	79.2	19.66	1577.07
100	200	> 100	9.83	> 983.0

Table 99 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 48.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	2.3	1966.00	4521.8
1.0	2	4.0	983.00	3932.0
2.5	5	9.5	393.20	3735.4
5	10	17.1	196.60	3361.86
10	20	30.1	98.30	2958.83
20	40	51.3	49.15	2521.40
50	100	93.7	19.66	1842.14
100	200	> 100	9.83	> 983.0

Table 100 : Gel viscosity measurement
Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 54.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	6.2	1966.00	12189.2
1.0	2	10.6	983.00	10419.8
2.5	5	22.0	393.20	8650.40
5	10	35.5	196.60	6979.30
10	20	55.8	98.30	5485.14
20	40	83.4	49.15	4099.11
50	100	>100	19.66	> 1966.6
100	200	> 100	9.83	> 983.0

Table 101 : Gel viscosity measurement
Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 60.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	14.6	1966.00	28703.60
1.0	2	24.4	983.00	23985.20
2.5	5	46.5	393.20	18283.80
5	10	73.0	196.60	14351.80
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.6
100	200	> 100	9.83	> 983.0

Table 102 : Gel viscosity measurement

Temperature = 40 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 72.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.6
100	200	> 100	9.83	> 983.0

Table 103 : Gel viscosity measurement

Temperarture = 60 ° C
Polymer concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.6	196.60	117.96
10	20	1.2	98.30	117.96
20	40	2.1	49.15	103.23
50	100	4.9	19.66	96.33
100	200	9.2	9.83	90.44

Table 104 : Gel viscosity measurement
Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.7	196.60	137.62
10	20	1.3	98.30	127.79
20	40	2.6	49.15	127.79
50	100	7.2	19.66	121.89
100	200	12.1	9.83	118.94

Table 105 : Gel viscosity measurement
Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.2	983.00	196.6
2.5	5	0.4	393.20	157.28
5	10	0.8	196.60	157.28
10	20	1.6	98.30	157.28
20	40	3.2	49.15	157.28
50	100	8.0	19.66	157.28
100	200	13.7	9.83	134.67

Table 106 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.2	1966.00	393.2
1.0	2	0.3	983.00	294.9
2.5	5	0.7	393.20	275.24
5	10	1.3	196.60	255.58
10	20	2.4	98.30	235.92
20	40	4.7	49.15	231.01
50	100	9.6	19.66	188.74
100	200	17.6	9.83	173.01

Table 107 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 6.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.3	1966.00	589.8
1.0	2	0.5	983.00	491.5
2.5	5	0.9	393.20	353.88
5	10	1.7	196.60	334.22
10	20	2.9	98.30	285.07
20	40	5.1	49.15	250.67
50	100	10.3	19.66	202.50
100	200	18.7	9.83	183.82

Table 108 : Gel viscosity measurement

Temperature = 60 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 9.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.6
100	200	> 100	9.83	> 983.0

Table 109 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 0.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.2	983.00	196.6
2.5	5	0.2	393.20	78.64
5	10	0.3	196.60	58.98
10	20	0.4	98.30	39.32
20	40	0.6	49.15	29.49
50	100	1.2	19.66	23.59
100	200	2.2	9.83	21.63

Table 110 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 0.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	0.1	1966.00	196.6
1.0	2	0.1	983.00	98.3
2.5	5	0.1	393.20	39.32
5	10	0.2	196.60	39.23
10	20	0.2	98.30	19.66
20	40	0.4	49.15	24.58
50	100	1.0	19.66	19.66
100	200	1.9	9.83	18.68

Table 111 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 1.5

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	1.1	1966.00	2162.6
1.0	2	1.7	983.00	1671.1
2.5	5	2.5	393.20	983.0
5	10	2.8	196.60	550.48
10	20	4.2	98.30	412.86
20	40	7.4	49.15	363.71
50	100	14.3	19.66	281.14
100	200	23.3	9.83	229.04

Table 112 : Gel viscosity measurement

Temperature = 90 ° C
Polyacrylamide concentration = 6.0 %
Chromium acetate concentration = 0.2 %
Sodium lactate concentration = 3.0
Time (hours) = 3.0

RPM	Shear Rate (S-1)	Display Reading (1)	Factor (cp) (2)	Viscosity (cps) 1 X 2
0.5	1	> 100	1966.00	> 196600.0
1.0	2	> 100	983.00	> 98300.0
2.5	5	> 100	393.20	> 39320.0
5	10	> 100	196.60	> 19660.0
10	20	> 100	98.30	> 9830.0
20	40	> 100	49.15	> 4915.0
50	100	> 100	19.66	> 1966.6
100	200	> 100	9.83	> 983.0

APPENDIX D

APPENDIX D

CORE FLOODING

Table 113 : Brine injection
Core number = 1
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	0.75
1.0	1.0	0.73
1.5	1.5	0.98

Table 114 : Gel injection
Core = 1
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 2.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	81.3
1.0	1.1	115.0
1.5	1.6	145.5

Table 115 : Displacing polymer by brine
Core number = 1
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	560.0
1.0	1.0	975.0
1.5	1.5	1300.0

Table 116 : Brine injection
Core number = 2
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.7	0.18
1.0	1.0	0.34
1.5	1.7	0.57

Table 117 : Gel injection
Core = 2
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 1.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	60.0
1.0	1.0	100.0
1.5	1.5	140.0

Table 118 : Displacing polymer by brine
Core number = 2
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.7	337.0
1.0	1.2	440.0
1.5	1.6	530.0

Table 119 Brine injection
Core number = 3
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.7	0.63
1.0	1.2	1.26
1.5	1.6	2.80

Table 120 : Gel injection
Core = 3
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 1.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	45.0
1.0	1.1	80.0
1.5	1.6	120.0

Table 121 : Displacing polymer by brine
Core number = 3
At temperature = 90 ° C

Set tate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	104.0
1.0	1.2	131.0
1.5	1.7	154.0

Table 122 : Brine injection
Core number = 4
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	0.15
1.0	1.0	0.30
1.5	1.7	0.49

Table 123 : Gel injection
Core = 4
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 3.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	30.0
1.0	1.1	60.0
1.5	1.6	90.0

Table 124 : Displacing polymer by brine
Core number = 4
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	46.0
1.0	1.1	82.0
1.5	1.7	107.0

Tabe 126 : Brine injection
Core number = 5
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	0.35
1.0	1.1	0.84
1.5	1.6	1.36

Table 127 : Gel injection
Core = 5
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 2.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	35.0
1.0	1.1	70.0
1.5	1.7	100.0

Table 128 : Displacing polymer by brine
Core number = 5
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	285.0
1.0	1.1	360.0
1.5	1.5	415.0

Tabel 129 : Brine injection
Core number = 6
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	0.36
1.0	1.2	0.63
1.5	1.7	1.08

Tabe 130 : Gel injection
Core = 6
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 2.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	not recorded	not recorded
1.0	not recorded	not recorded
1.5	not recorded	not recorded

Table 131 : Displacing polymer by brine
Core number = 6
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	530.0
1.0	1.1	640.0
1.5	1.5	752.0

Table 132 : Brine injection
Core number = 7
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.7	0.30
1.0	1.2	0.67
1.5	1.6	0.90

Table 133 : Gel injection
Core = 7
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 3.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	140.0
1.0	1.0	200.0
1.5	1.5	270.0

Table 134 : Displacing polymer by brine
Core number = 7
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	6.0
1.0	1.1	14.0
1.5	1.6	16.0

Table 135 : Brine injection
Core number = 8
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.6	0.75
1.0	1.1	1.65
1.5	1.6	2.50

Table 136 : Gel injection

Core = 8
Chromium acetate concentration = 0.2 %
Polyacrylamide concentration = 6.0 %
Sodium lactate concentration = 1.0 %
At temperature = 25 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	45.0
1.0	1.0	90.0
1.5	1.6	145.0

Table 137 : Displacing polymer by brine

Core number = 8
At temperature = 90 ° C

Set rate (cc / min)	Volume collected (cc / min)	Pressure drop (psi)
0.5	0.5	12.0
1.0	1.0	28.0
1.5	1.5	36.0